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DMIC Report 189
September 13, 1963

THE ENGINEERING PROPERTIES OF TANTALUM AND TANTALUM ALLOYS

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

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1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

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DMIC Report 189
September 13, 1963

THE ENGINEERING PROPERTIES OF TANTALUM AND TANTALUM ALLOYS

by

F. F. Schmidt and H. R. Ogden

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

FOREWORD

The growing interest in the use of columbium, molybdenum, tantalum, and tungsten metals and their alloys for structural applications has emphasized the need for an up-to-date review of some of the more important physical, mechanical, and metallurgical properties of these materials. Four consecutively numbered reports covering columbium and columbium alloys, molybdenum and molybdenum alloys, tantalum and tantalum alloys, and tungsten and tungsten alloys have been prepared. The intent of these reports has been to assemble, present, and summarize, in easy reference form, the engineering-property data of these four refractory metals and alloys. This report covers tantalum and tantalum alloys.

In addition to data available from the published literature, numerous organizations have contributed data for inclusion in this report. The Defense Metals Information Center gratefully acknowledges the assistance of the following individuals and organizations who contributed valuable information used in the preparation of this report.

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THE ENGINEERING PROPERTIES OF
TANTALUM AND TANTALUM ALLOYS

SUMMARY

This report presents the results of a state-of-the-art survey covering tantalum and seven of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

INTRODUCTION

The requirements for structural materials for service temperatures in excess of those attainable with present materials of construction has provided the stimulus for the development of refractory metals and alloys. Interest has stemmed largely from the high-temperature structural-engineering requirements associated with military hardware. In the development of the refractory metals, columbium, molybdenum, tantalum, and tungsten, and their alloys, extensive studies have been conducted and are in progress which are aimed toward the investigation of fundamental metallurgical concepts, alloy development, pilot scale-up development of promising compositions, and, ultimately, alloy commercialization.

This report reviews some of the more important properties of tantalum and seven of its alloys. Of this group of alloys, several have not reached true commercial status; however the potential of these advanced experimental and pilot-production alloys warrants consideration. All data are presented in tabular and graphical form according to a number of important physical, mechanical, and metallurgical properties for tantalum and each of its seven alloys. Properties and alloys covered in this report are listed in Table 1.

Tantalum is the most recent of the refractory metals to undergo extensive study. Present work includes attempts to improve basic high-temperature strength capabilities through both solution and dispersion strengthening while maintaining cryogenic ductility. Efforts have also been directed toward the addition of lighter elements to improve the strength-to-weight ratio.

In preparing this state-of-the-art survey, technical journals and publications, research reports, and trade literature made available to the Defense Metals Information Center were supplemented with personal contacts with a number of individuals and organizations actively engaged in the refractory-metals field. References are given at the conclusion of each material section.

TABLE 1. ALLOYS AND PROPERTY DATA COVERED IN THIS REPORT

Alloy Composition	Identification of Material	Designation	Chemical Composition	Forms Available	Physical Properties	Melting Point	Density	Thermal Expansion	Thermal Conductivity	Electrical Resistivity	Mechanical Properties	Tensile Properties	Ultimate Tensile Strength	Tensile Yield Strength	Elongation	Reduction in Area	Modulus of Elasticity	Notched Tensile Properties	Creep and Stress-Rupture Properties	Other Selected Mechanical Properties	Metallurgical Properties	Fabricability	Transition Temperature	Weldability	Stress-Relief Temperature	Recrystallization Temperature
Tantalum		x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x		x	x	x	x	x
Ta-10W		x	x	x		x	x	x	x				x	x	x	x	x	x	x	x		x	x	x	x	x
Ta-12.5W		x	x	x		x	x						x	x	x					x		x	x	x	x	x
Ta-30Cb-7.5V			x	x		x	x						x	x	x		x			x		x	x	x	x	x
Ta-5W-2.5Mo			x	x			x						x	x	x				x	x		x	x	x	x	x
Ta-8W-2Hf		x	x	x		x	x	x		x			x	x	x		x		x			x	x	x	x	x
Ta-10W-2.5Hf		x	x	x			x						x	x	x	x						x		x	x	x
Ta-10W-2.5Mo			x	x			x						x	x	x				x	x		x	x	x	x	x

ORGANIZATION OF DATA PRESENTED IN THE APPENDIX

1. Identification of Material

    Designation
    Chemical composition
    Forms available

2. Physical Properties

    Melting point
    Density
    Thermal expansion
    Thermal conductivity
    Electrical resistivity

3. Mechanical Properties

    Tensile Properties at Room Temperature

        Ultimate tensile strength
        Tensile yield strength
        Elongation
        Reduction in area
        Modulus of elasticity

    Effect of Temperature on Tensile Properties

        Ultimate tensile strength
        Tensile yield strength
        Elongation
        Reduction in area
        Modulus of elasticity

    Notched Tensile Properties

    Creep and Stress-Rupture Properties

    Other Selected Mechanical Properties

4. Metallurgical Properties

    Fabricability
    Transition temperature
    Weldability
    Stress-relief temperature
    Recrystallization temperature

References

APPENDIX

TANTALUM AND ITS ALLOYS

APPENDIX

TANTALUM AND ITS ALLOYS

Unalloyed Tantalum

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: Tables A-1 through A-3

   c. Forms available: ingot, bar, plate, sheet, strip, foil, rod, and wire[1, 2]

TABLE A-1. CHEMICAL REQUIREMENTS FOR POWDER-METALLURGY, ARC-CAST, AND ELECTRON-BEAM-CAST TANTALUM(a)(1, 2)

Element	Impurity Content(b), Maximum, weight per cent
C	0.03
O	0.03
N	0.015
H	0.01
Cb	0.10
Fe	0.02
Ti	0.01
W	0.03
Si	0.02
Ni	0.02

(a) For ingot, bar, plate, sheet, strip, foil, rod, and wire products.
(b) The total of all impurities shall not be over 0.2 per cent.

TABLE A-2. PURITY RANGES SPECIFIED FOR TANTALUM POWDERS

Element	Impurity Content, weight per cent	
	Sintered Product(3)	Melted Product(4)
C	0.10	0.0025-0.04
O	0.17	0.035-0.08
N	0.01	0.002-0.02
H	--	0.005-0.05
Al	<0.02	<0.0025-0.005
Cb	0.03	0.0025-0.05
Fe	0.015	0.005-0.01
Mo	0.003	<0.001-0.008
Ni	<0.002	0.003-0.006
Si	0.02	0.02-0.03

TABLE A-3. REPRESENTATIVE ANALYSES OF TANTALUM AS PRODUCED BY VARIOUS PROCESSES

Element	Impurity Content, ppm		
		Ingot, Made by	
	Powder-Metal Product(3)	Consumable-Electrode Process(5)	Electron-Beam Process(6)
C	30	23-30	30-60
O	100	34-65	<50
N	<100	27	39-43
H	--	1-5	3
Al	[illegible]	--	<20
Cr	--	14	<20
Cu	--	--	<40
Fe	100	30	<100
Ni	<200	28	<20
Mo	<30	--	<20
Si	<200	30	<100

2. Physical Properties

a. Melting point: 5425 F[7]

b. Density: 0.600 lb/in.^{3}[7]

c. Thermal expansion: Tables A-4 and A-5

d. Thermal conductivity: Figures A-1 and A-2

e. Electrical resistivity: Figures A-3 and A-4

TABLE A-4. LINEAR THERMAL EXPANSION OF TANTALUM[8]

Temperature, C	Linear Expansion[a], per cent
127	0.07
327	0.20
527	0.34
727	0.48
927	0.61
1127	0.81
1327	0.99
1527	1.16
1727	1.34
1927	1.53
2127	1.72
2327	1.93
2527	2.15
2727	2.40
2927	2.69

(a) The linear coefficient of thermal expansion can be expressed by the following equation:

$$a \times 10^{6} = 6.5 + 0.34 \times 10^{-3}\, t + 0.12 \times 10^{-6}\, t^{2},$$

where

a = per degree, C

t = temperature, C.

TABLE A-5. THERMAL EXPANSION OF TANTALUM SUPPLIED BY FANSTEEL METALLURGICAL AND NATIONAL RESEARCH[a][9]

Temp, C	Linear Expansion, per cent	Coefficient, 27 C to Temp, 10^{-6}/C	Temp, F	Linear Expansion, per cent	Coefficient, 85 F to Temp, 10^{-6}/F
1600	1.04	6.61	3000	1.09	3.74
1800	1.23	6.93	3400	1.30	3.92
2000	1.45	7.35	3800	1.56	4.20
2200	1.71	7.88	4200	1.88	4.56
2400	2.04	8.60	4600	2.33	5.15
2600	2.47	9.61	5000	2.88	5.86
2800	2.99	10.79	5200	3.18	6.21
2900	3.26	11.35			

(a) Composition, per cent, Balance Tantalum

Producer	C	Fe	Si	Mo	Cb	N	O	H	Others
Fansteel	0.008	0.005	<0.02	0.003	--	--	--	--	<0.05
NRC	0.0016	0.0028	--	--	0.0035	0.001	0.0032 0.005	--	0.0175

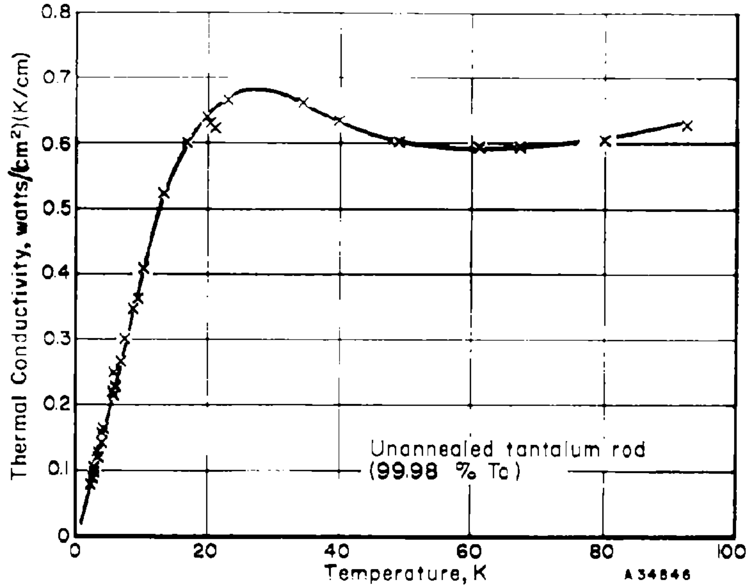


FIGURE A-1. THERMAL CONDUCTIVITY OF TANTALUM AT LOW TEMPERATURES[10]

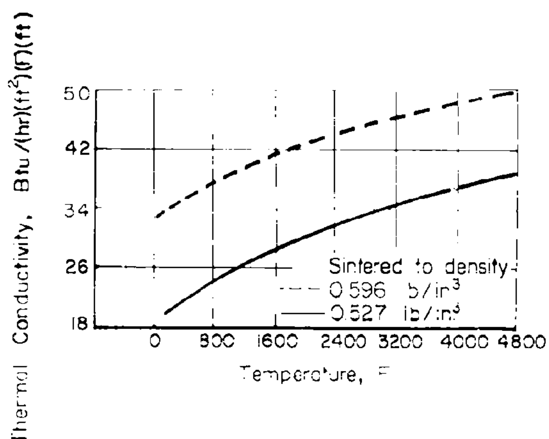


FIGURE A-2. THERMAL CONDUCTIVITY OF COMMERCIAL-PURITY TANTALUM[11]

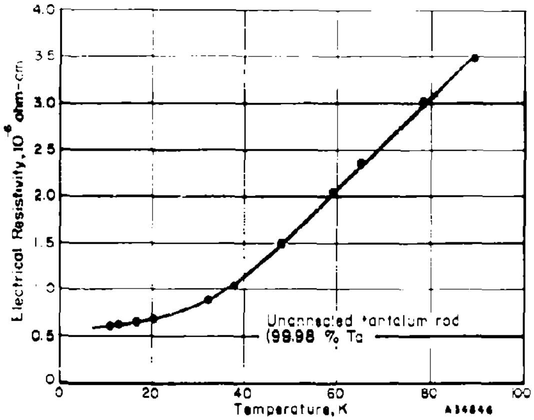


FIGURE A-3. ELECTRICAL RESISTIVITY OF TANTALUM AT LOW TEMPERATURES(10)

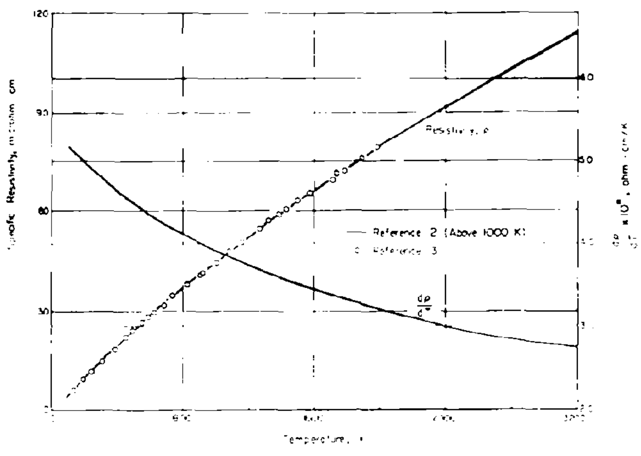


FIGURE A-4. ELECTRICAL RESISTIVITY OF TANTALUM AND ITS TEMPERATURE COEFFICIENT

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-6 and A-7

Tensile yield strength: Table A-8

Elongation: Tables A-6 through A-8

Reduction in area: Table A-8

Modulus of elasticity: 27×10^6 psi[8]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-9 through A-13
Figures A-5 through A-7

Tensile yield strength: Tables A-9 through A-13
Figures A-6 and A-7

Elongation: Tables A-9 through A-13
Figures A-5 through A-7

Reduction in area: Table A-9

Modulus of elasticity: Tables A-12 and A-13
Figures A-7 and A-8

c. Notched Tensile Properties

Figures A-9 through A-16

d. Creep and Stress-Rupture Properties

Figures A-17 through A-20

e. Other Selected Mechanical Properties

Impact: Figure A-21

Fatigue: Figures A-22 and A-23

TABLE A-6. MINIMUM TENSILE-PROPERTY REQUIREMENTS FOR POWDER-METALLURGY, ARC-CAST, AND ELECTRON-BEAM-CAST TANTALUM INGOTS AND FLAT MILL PRODUCTS(a)(1)

Condition	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent: Specimens 0.021 In. Thick and Over	Elongation in 2 Inches, per cent: Specimens 0.020 In. Thick and Under
Cold worked	75	2	2
Stress relieved	55	10	7.5
Full annealed	--	30	25

(a) For bar, plate, sheet, strip, and foil. Tensile properties shall be determined using a strain rate of 0.005 inch per inch per minute through 0.6 per cent offset, and 0.02 to 0.05 inch per inch per minute to fracture.

TABLE A-7. MINIMUM TENSILE-PROPERTY REQUIREMENTS FOR POWDER-METALLURGY, ARC-CAST, AND ELECTRON-BEAM-CAST TANTALUM ROD AND WIRE(a)(2)

Condition	Tensile Strength, 1000 psi	Elongation, per cent	Gage Length, inches
Cold worked	70	1	10
Annealed, commercial purity	--	10	10
Annealed, high purity	--	20	10

(a) Crosshead speed to be used is 2 per cent of gage length per minute.

TABLE A-8. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM[8]

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
Recrystallized[a]	27.5	--	38	89
Recrystallized high-purity sheet (1 hr at 2190 F; 0.040 inch thick)	29.4	26.3	36	--
Recrystallized rod (1 hr at 2600 F)[c]	33.5	--	50	--
Recrystallized sheet	40.0/50.0	30.0/40.0	30/40	--
Recrystallized rod (1 hr at 3090 F)[d]	49.8	39.3	45	86
Annealed sheet (0.010 inch thick)	50.0	--	40	--
Cold-worked high-purity sheet (cold reduced 95%; 0.040 inch thick)[b]	60.5	49.0	--	--
Recrystallized sheet (0.010 inch thick)[e]	67.1	57.4	25	--
Annealed wire (0.002-inch diameter)	100.0	--	11	--
Cold-worked sheet	100.0/120.0	95.0/105.0	3	--
Cold-worked sheet (0.010 inch thick)	1 0.0	--	1	--
Hardened plate (0.010 inch thick)	145.0	--	18	--
As-drawn wire (0.002-inch diameter)	180.0	--	2	--

(a) Degassed: <0.01% C.

(b) Electron-beam-melted tantalum supplied by Temescal Metallurgical Corporation: 0.0016% O, 0.0010% N, 0.00014% H, 0.0030% C, 0.0003% Cr, 0.01-0.03% Cb, 0.003% Cu, 0.0008% Fe, 0.0003% Ni.

(c) From hydrogen-reduced powder: 99.98% Ta, traces of Ni, Fe, W, Cu, Ca, Si, Pb, Sn, Cr.

(d) Supplied by Fansteel Metallurgical Corporation: 0.01% N, 0.010% C, 450 grains/mm^2.

(e) Powder-metallurgy ingots supplied by Fansteel Metallurgical Corporation: 0.0056% O, 0.013% N, 0.02% C, 0.10% Cb, 0.01% W, 0.015% Fe, 512-1024 grains/mm^2.

TABLE A-9. TENSILE PROPERTIES OF RECRYSTALLIZED TANTALUM ROD[a][14]

Temperature, F	Strain Rate, in./in./sec	Yield Strength[b], 1000 psi	Yield Point, 1000 psi Upper	Yield Point, 1000 psi Lower	Maximum Load: Tensile Strength, 1000 psi	Maximum Load: Uniform Elongation, per cent	Fracture: Total Elongation, per cent	Fracture: Total Reduction in Area, per cent
-320	2.8×10^{-4}	124.0	124.6	110.0	(c)	0	12	75
-320	9.2×10^{-3}	127.0	128.5	110.0	(c)	0	11	71
-320	6.0×10^{-1}	--	139.5	--	(c)	0	11	76
-290	2.8×10^{-4}	104.5	105.2	94.0	(c)	0	13	78
-200	2.8×10^{-4}	82.7	84.2	76.0	(c)	0	15	81
-100	2.8×10^{-4}	60.3	61.0	54.5	58.7	16	37	89
-22	2.8×10^{-4}	56.5	56.5	50.2	55.7	20	34	[illegible]
78	2.8×10^{-4}	39.3	(d)	39.7	49.8	25	45	83
340	2.8×10^{-4}	26.2	(d)	26.2	46.8	24	31	[illegible]
750	2.8×10^{-4}	22.4	(d)	22.4	52.2	18	27	84

(a) Commercial-purity recrystallized tantalum rod (1 hr at 1700 C; 450 grams/mm²); 0.01% N, 0.01% C.

(b) Yield strength defined as the stress at which the curve of load versus per cent elongation deviates from linearity.

(c) Specimens did not have ultimate tensile strengths in the usual significance attached to the term since the load did not increase after the yield-point elongation.

(d) No pronounced upper yield point, but a definite yield-point elongation.

TABLE A-10. TENSILE PROPERTIES OF RECRYSTALLIZED TANTALUM SHEET PRODUCED FROM POWDER-METALLURGY INGOT[(a)(16)]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
-320	148.0	148.0	4
-100	73.2	72.5	23
80	67.1	57.4	25
210	59.3	42.5	25
400	56.1	35.4	13
600	74.0	37.9	18
800	65.3	33.4	24
1000	59.9	26.1	16
1205	44.7	18.9	17
1400	30.3	16.9	23
15[illegible]	22.2	12.1	33
1800	21.6	12.4	33
2000	16.8	8.1	43
2200	14.7	7.5	48

(a) Recrystallized powder-metallurgy tantalum sheet (0.010 inch thick); strain rate 0.09 inch per inch per minute; 0.0056% O, 0.013% N, 0.02% C, 0.10% Cb, 0.01% W, 0.015% Fe, 512-1024 grains/mm^2, ASTM 6-7.

TABLE A-11. HIGH-TEMPERATURE TENSILE PROPERTIES OF ANNEALED TANTALUM SHEET[(a)(17)]

Temperature, F	Time at Temp, sec	Strain Rate, in./in./sec	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent
3000	10	0.1	10.70	7.49	30
	90	0.1	10.76	6.96	30
	10	0.00005	4.03	3.78	19
	90	0.00005	4.12	3.86	19
3500	10	0.00005	0.915	0.611	(b)
	90	0.00005	1.81	0.792	(b)
4000	10	0.1	3.69	1.76	44
	90	0.1	3.95	1.61	46
	90	0.00005	0.420	0.42	(b)
5000	10	0.1	2.43	1.29	48
	90	0.1	2.06	1.17	--

(a) Sintered, rolled, annealed, tantalum sheet. Specimens heated to test temperature in 20 seconds. Tests conducted in argon atmosphere. Values reported are average of at least three tests.
(b) Specimens were not strained to fracture.

TABLE A-12. HIGH-TEMPERATURE TENSILE PROPERTIES OF POWDER-METALLURGY-PRODUCED TANTALUM SHEET(a)(9)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Modulus of Elasticity, 10^6 psi	Load Rate, psi/sec	Elongation, per cent
3420	6.160	3.200	3.6	267	39
3670	5.110	2.550	0.6	197	46
3955	3.025	1.510	0.7	63	34
3955	2.740	1.850	0.2	16	32
4380	2.460	1.240	1.1	63	44
4380	2.640	--	--	66	38
4470	2.290	1.320	0.4	64	37
4525	2.650	1.350	1.5	54	34
4525	2.060	1.270	0.4	57	38
4985	1.870	1.140	0.4	67	25
5010	1.240	0.860	0.3	10	11
5100	0.977	0.800	0.1	7.5	13

(a) Powder-metallurgy-produced sheet (0.050 to 0.060 inch thick); 0.03% max C, 0.03% max Fe, <0.005% Si, 0.24% Mo, and <0.05% other impurities.

TABLE A-13. HIGH-TEMPERATURE TENSILE PROPERTIES OF ARC-MELTED TANTALUM SHEET(a)(9)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Proportional Limit, 1000 psi	Modulus of Elasticity, 10^6 psi	Load Rate, psi/sec	Elongation, per cent
3210	4.370	1.950	1.150	1.0	59	35
3690	3.800	1.550	1.450	0.3	146	47
3725	2.780	1.260	1.100	0.2	63	43
4345	2.380	0.600	0.450	0.04	92	47
4530	1.730	0.640	0.550	0.07	62	35
5015	0.705	0.360	--	--	9	26
5040	1.170	0.350	0.250	0.07	35	31

(a) Consumable-electrode, arc-melted tantalum sheet (0.060 inch thick); 0.0015% C, 0.0028% Fe, 0.0062% Cb, 0.0003-0.0008% H, 0.002-0.003% N, 0.0035-0.0059% O, and 0.173% other impurities.

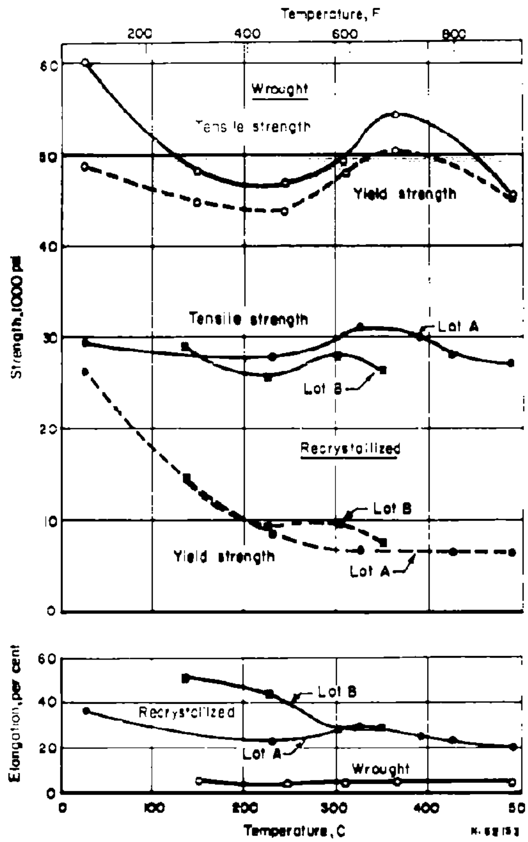


FIGURE A-5. TENSILE PROPERTIES OF ELECTRON-BEAM-MELTED TANTALUM SHEET (0.040 INCH)[15]

Impurity	Weight Per Cent
C	0.0030
O	0.0016
N	0.0010
Others	<0.040

Crosshead speed: 0.05 inch per minute for a 1-1/4-inch reduced section

Wrought: Cold rolled 75 per cent and stress relieved 1/4 hour at 1350 F

Recrystallized: Cold rolled 75 per cent and recrystallized 1 hour at 2190 F.

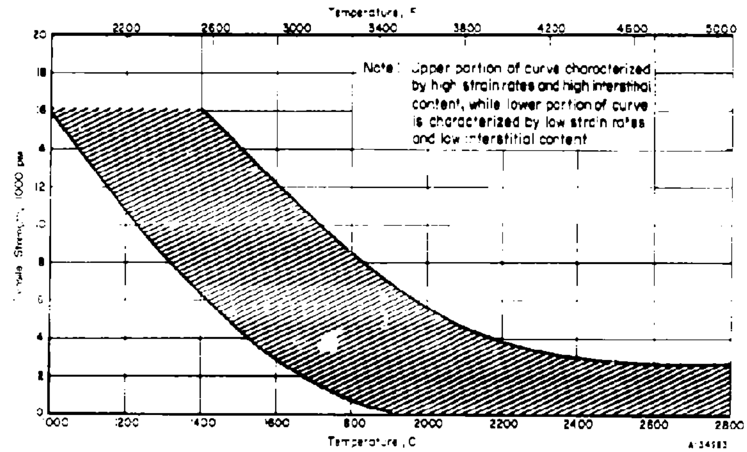


FIGURE A-6. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF TANTALUM(8)

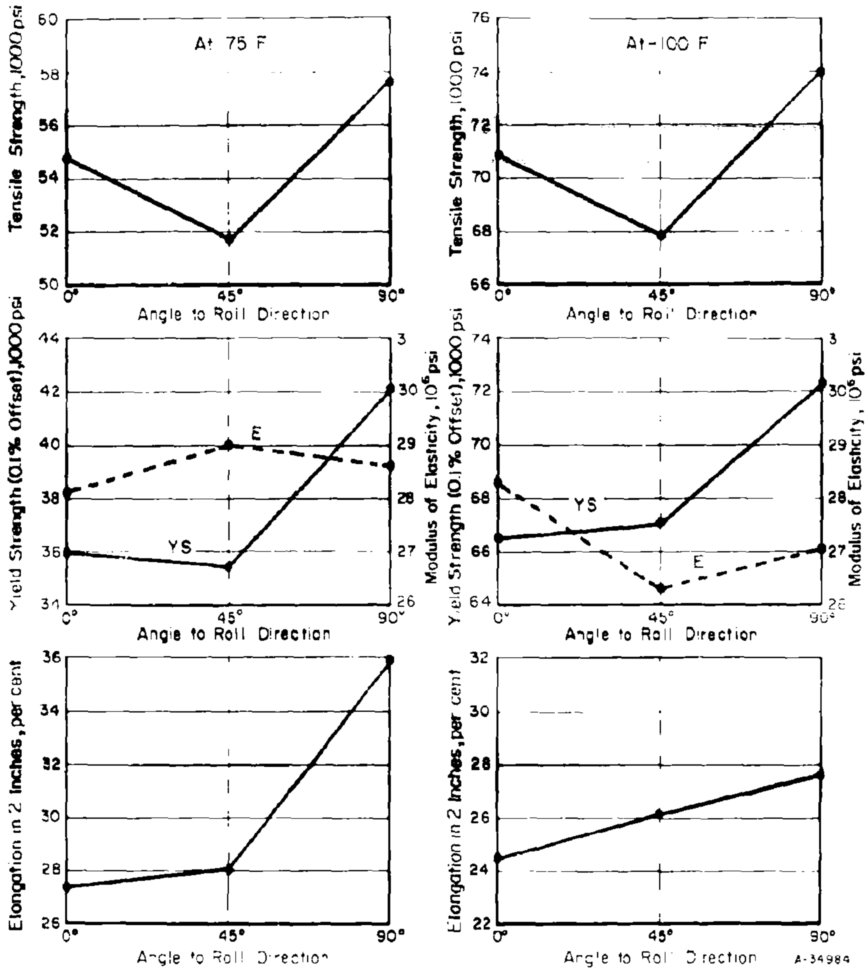


FIGURE A-7. TENSILE-PROPERTY DIRECTIONALITY OF ANNEALED (1 HOUR 2550 F) TANTALUM SHEET (0.02 INCH)[18]

Test rate 0.002 inch per inch per minute.

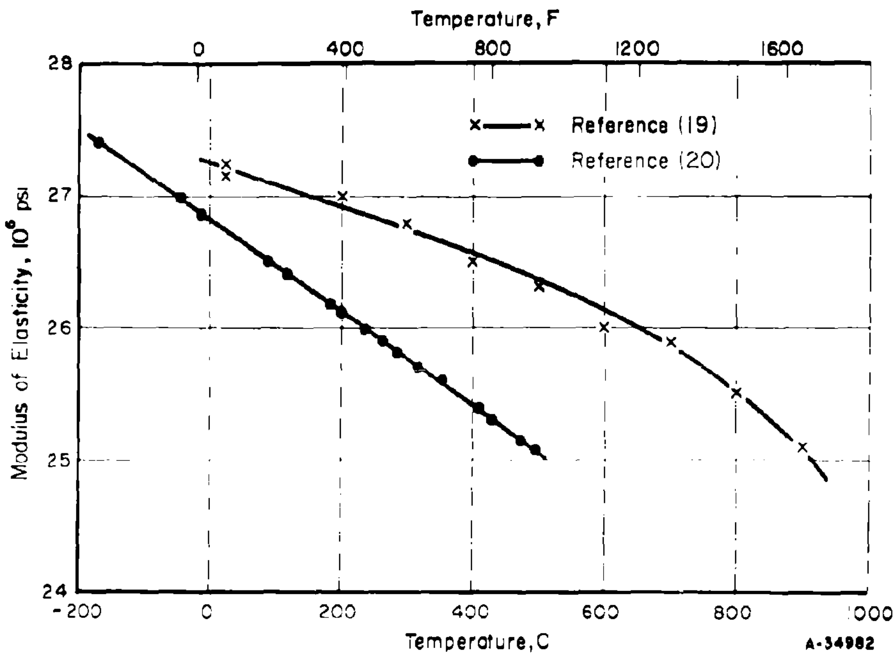


FIGURE A-8. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF TANTALUM

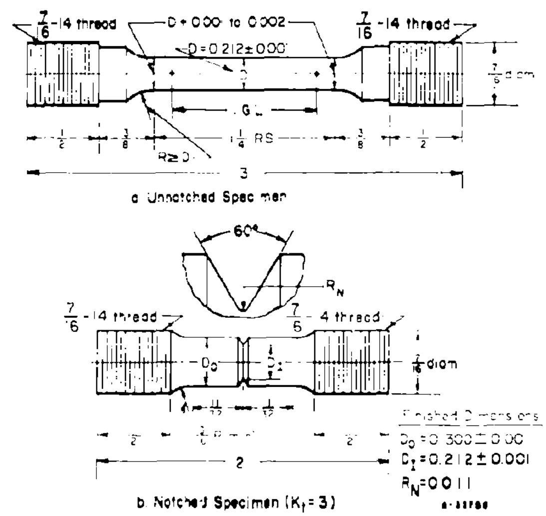


FIGURE A-9. UNNOTCHED AND NOTCHED BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-10 AND A-11

All dimensions are in inches.

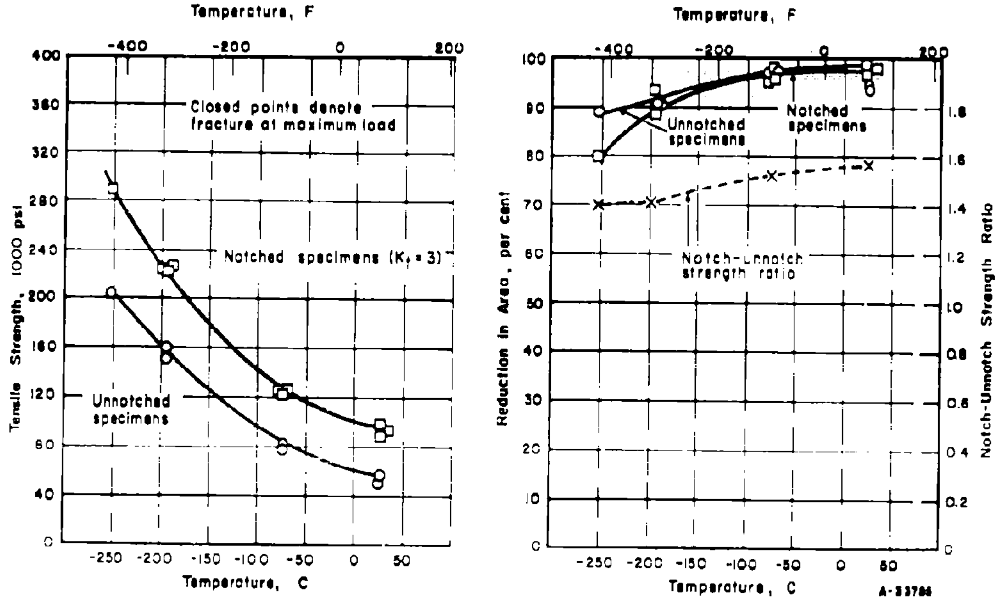


FIGURE A-10. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED, ELECTRON-BEAM-MELTED TANTALUM BAR (1 HR AT 750 C; HARDNESS 145 VHN)(21)

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Impurity	Weight Per Cent
C	<0.003
O	<0.003
N	0.0008
Others	<0.08

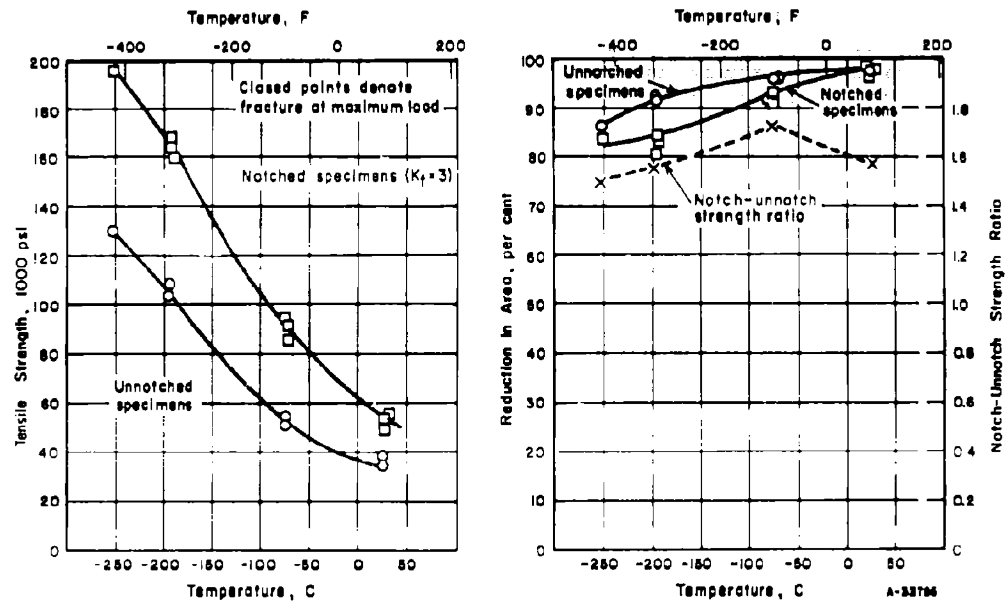


FIGURE A-11. TENSILE PROPERTIES FOR RECRYSTALLIZED, ELECTRON-BEAM-MELTED TANTALUM BAR (3 HR AT 1200 C; HARDNESS 83 VHN; ASTM 4, 8)[21]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Impurity	Weight Per Cent
C	<0.003
O	<0.003
N	0.0008
Others	<0.05

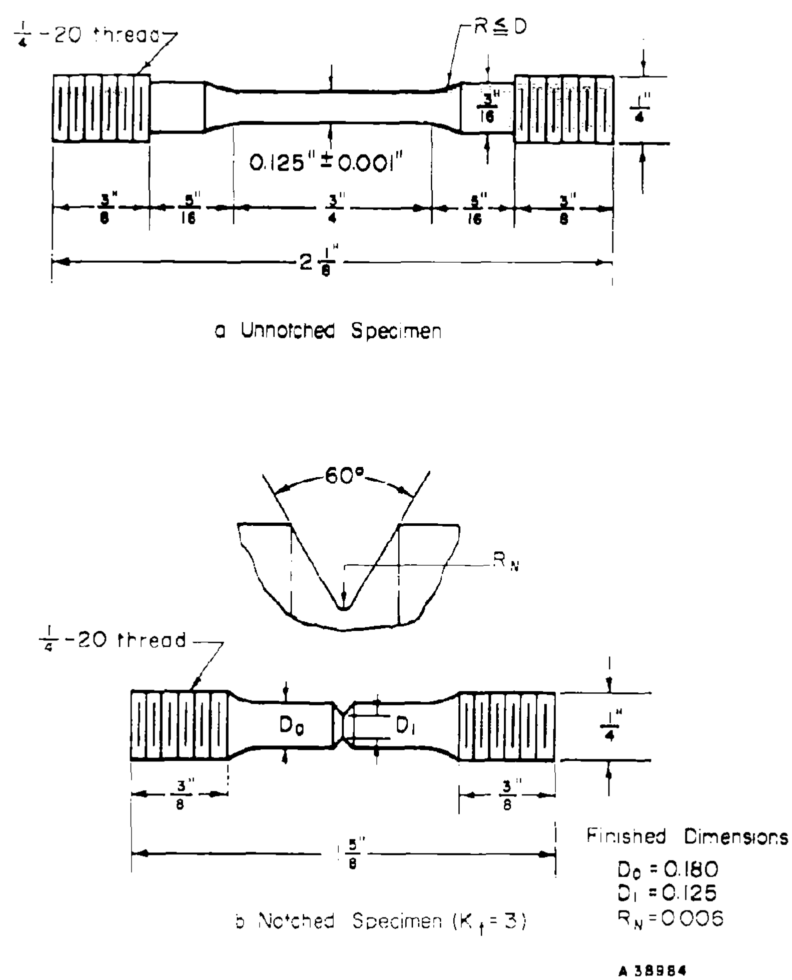


FIGURE A-12. UNNOTCHED AND NOTCHED-BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-13 THROUGH A-16

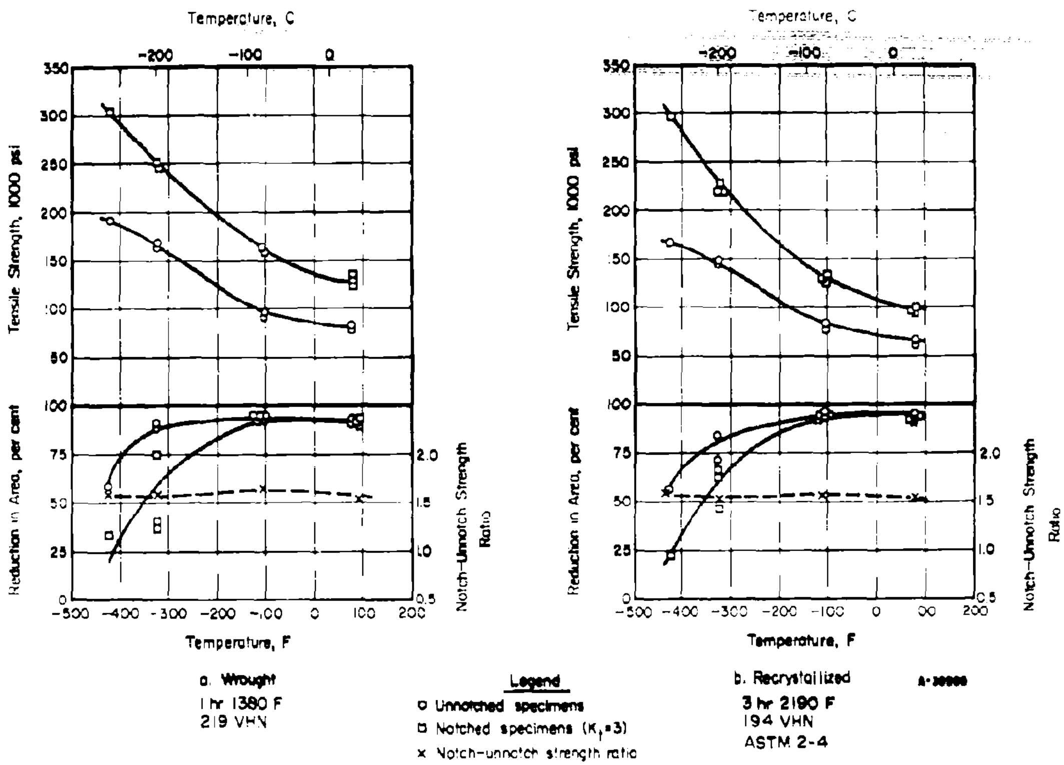


FIGURE A-13. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED TANTALUM BAR CONTAINING 489 PPM OXYGEN AND 5 PPM HYDROGEN(22)

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Bar material <44 ppm combined carbon and nitrogen.

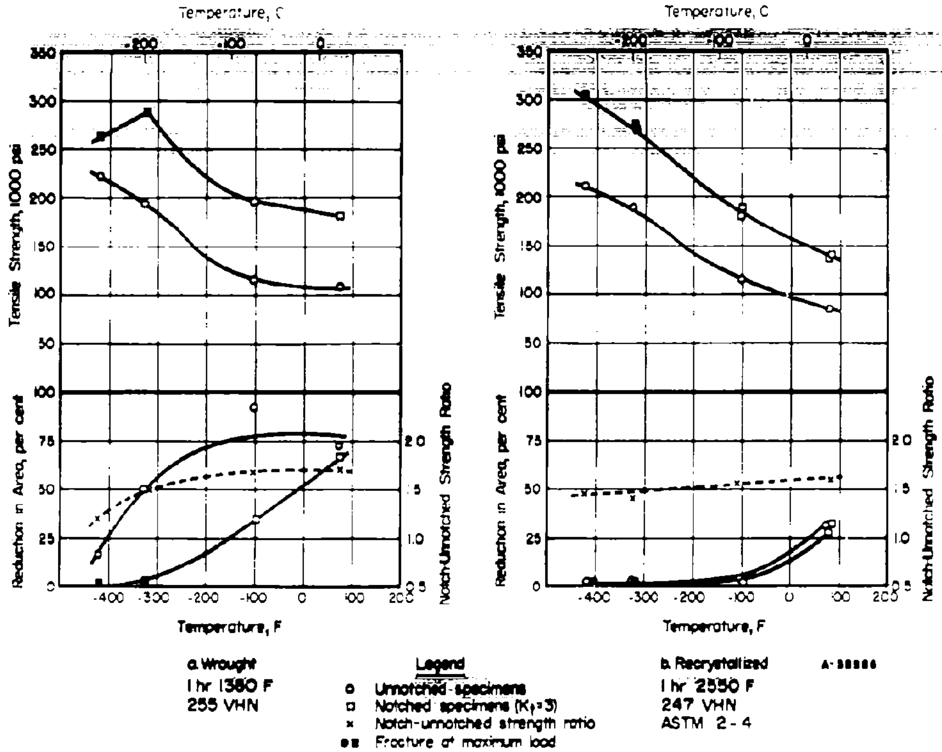


FIGURE A-14. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED TANTALUM BAR CONTAINING 758 PPM OXYGEN AND 4 PPM HYDROGEN[22]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Bar material <44 ppm combined carbon and nitrogen.

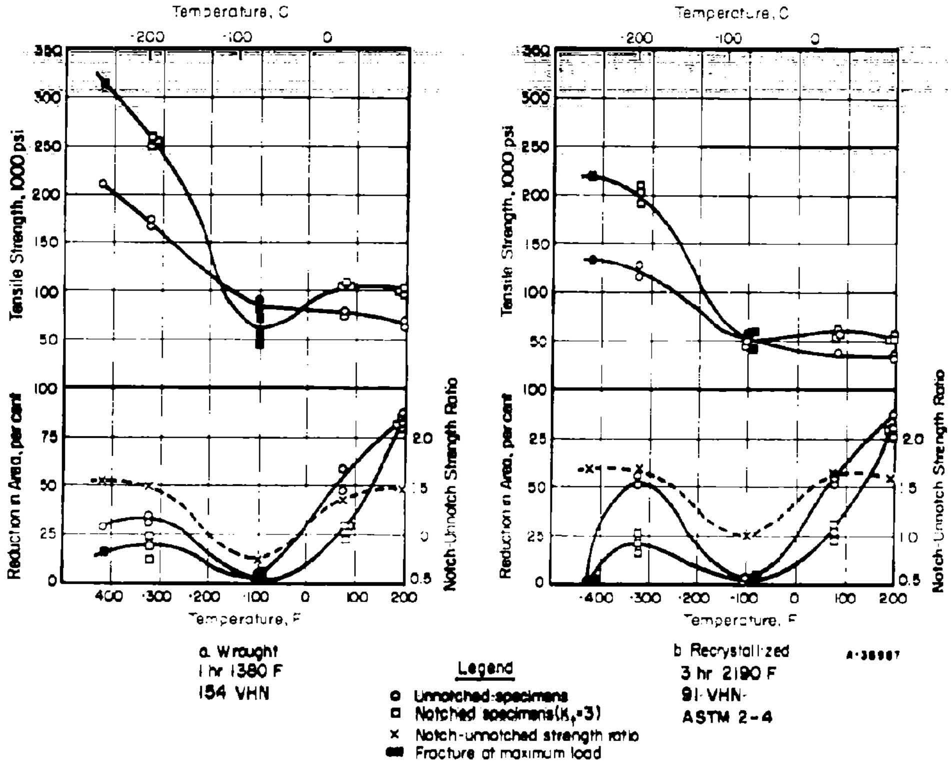


FIGURE A-15. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED TANTALUM BAR CONTAINING 82 PPM OXYGEN AND 135 PPM HYDROGEN[22]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Bar material <44 ppm combined carbon and nitrogen.

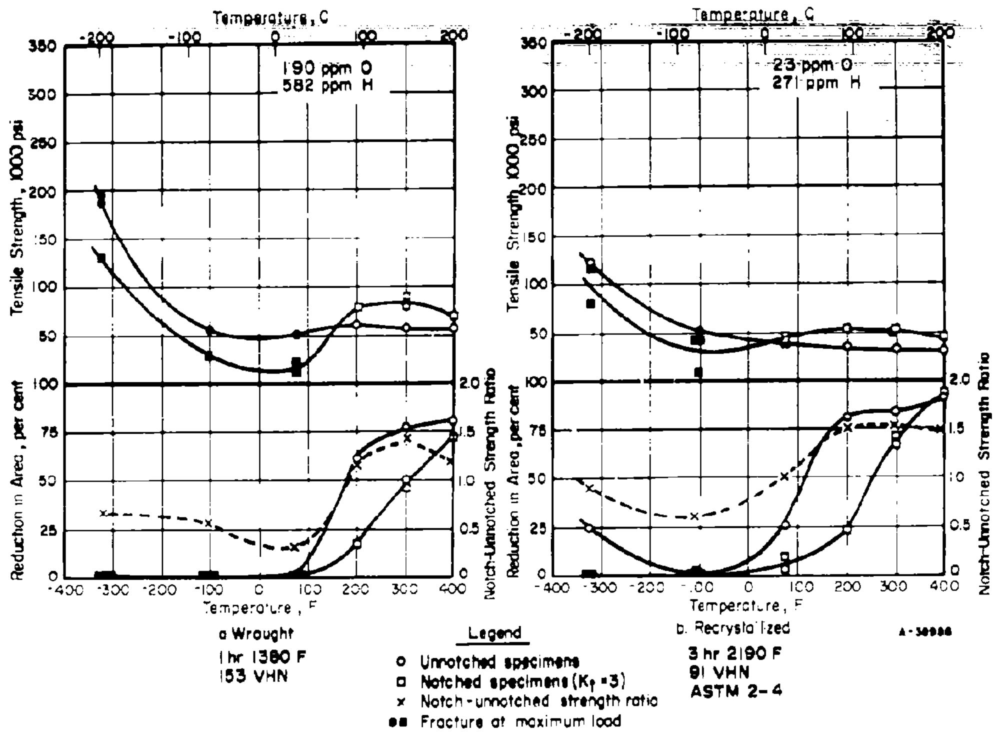
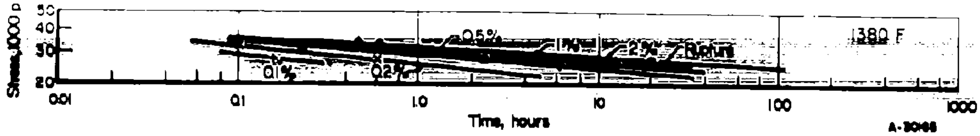


FIGURE A-16. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED TANTALUM BAR CONTAINING "HIGH" HYDROGEN[22]

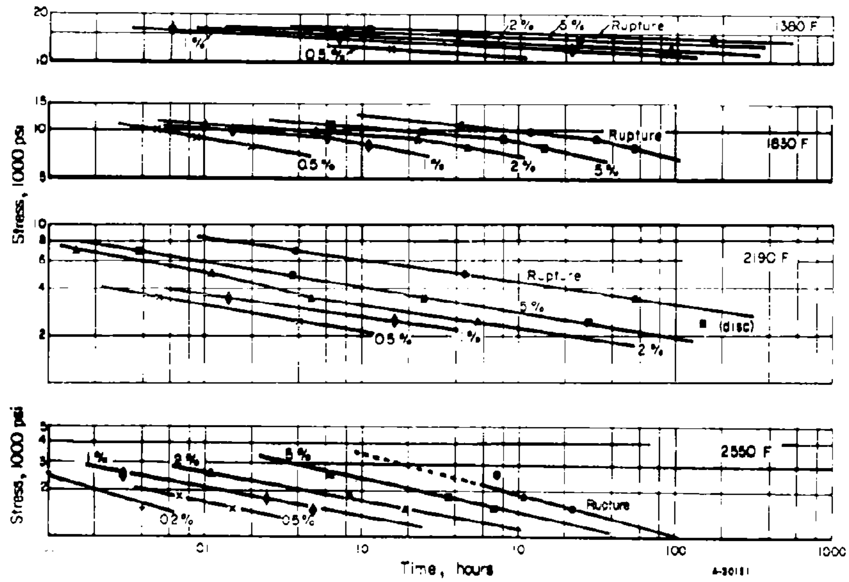
	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Bar material <44 ppm combined carbon and nitrogen.



a. Wrought

Cold rolled 95 per cent and stress relieved $\frac{1}{4}$ hour at 1380 F



b. Recrystallized

Cold rolled 75 per cent and recrystallized 1 hour at 2190 F

FIGURE A-17. CREEP AND RUPTURE CURVES FOR RECRYSTALLIZED ELECTRON-BEAM-MELTED TANTALUM SHEET (0.040 INCH)(15)

Impurity	Weight Per Cent
C	0.0030
O	0.0016
N	0.0010
Others	<0.040

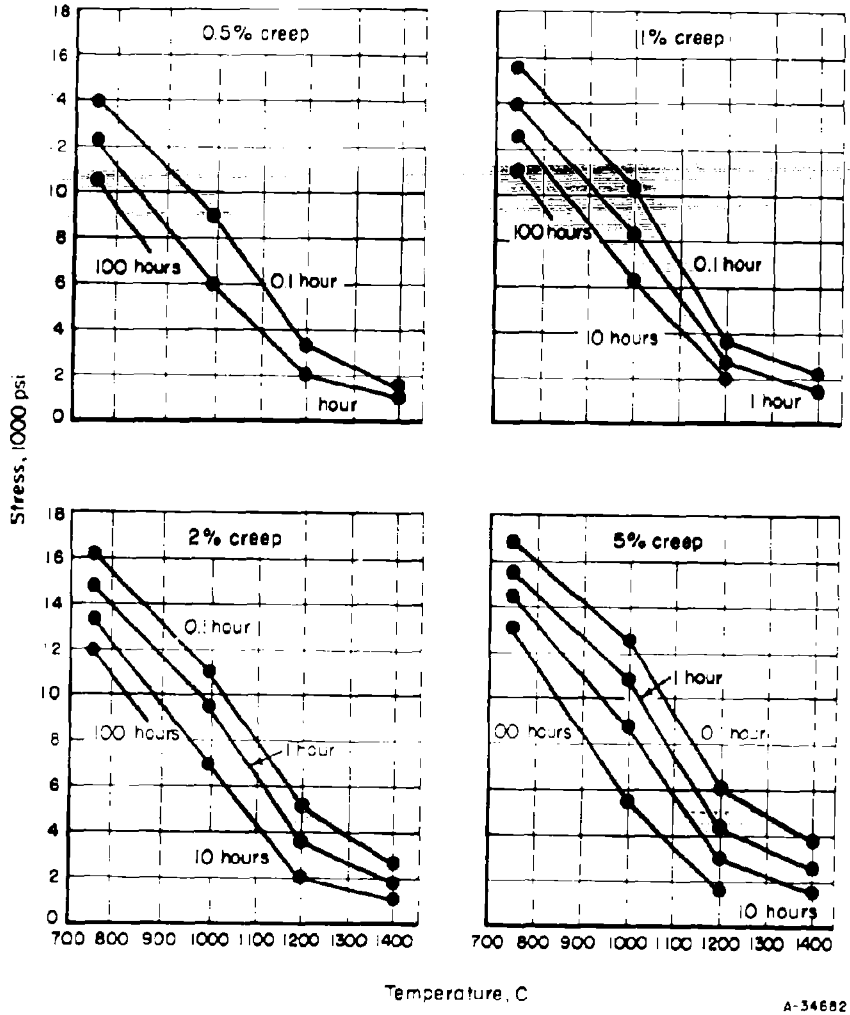


FIGURE A-18. EFFECT OF TEMPERATURE ON THE CREEP STRENGTH OF RECRYSTALLIZED ELECTRON-BEAM-MELTED TANTALUM SHEET (0.040 INCH)[15]

Cold rolled 75 per cent and recrystallized 1 hour at 2190 F.

Impurity	Weight Per Cent
C	0.0030
O	0.0016
N	0.0010
Others	<0.040

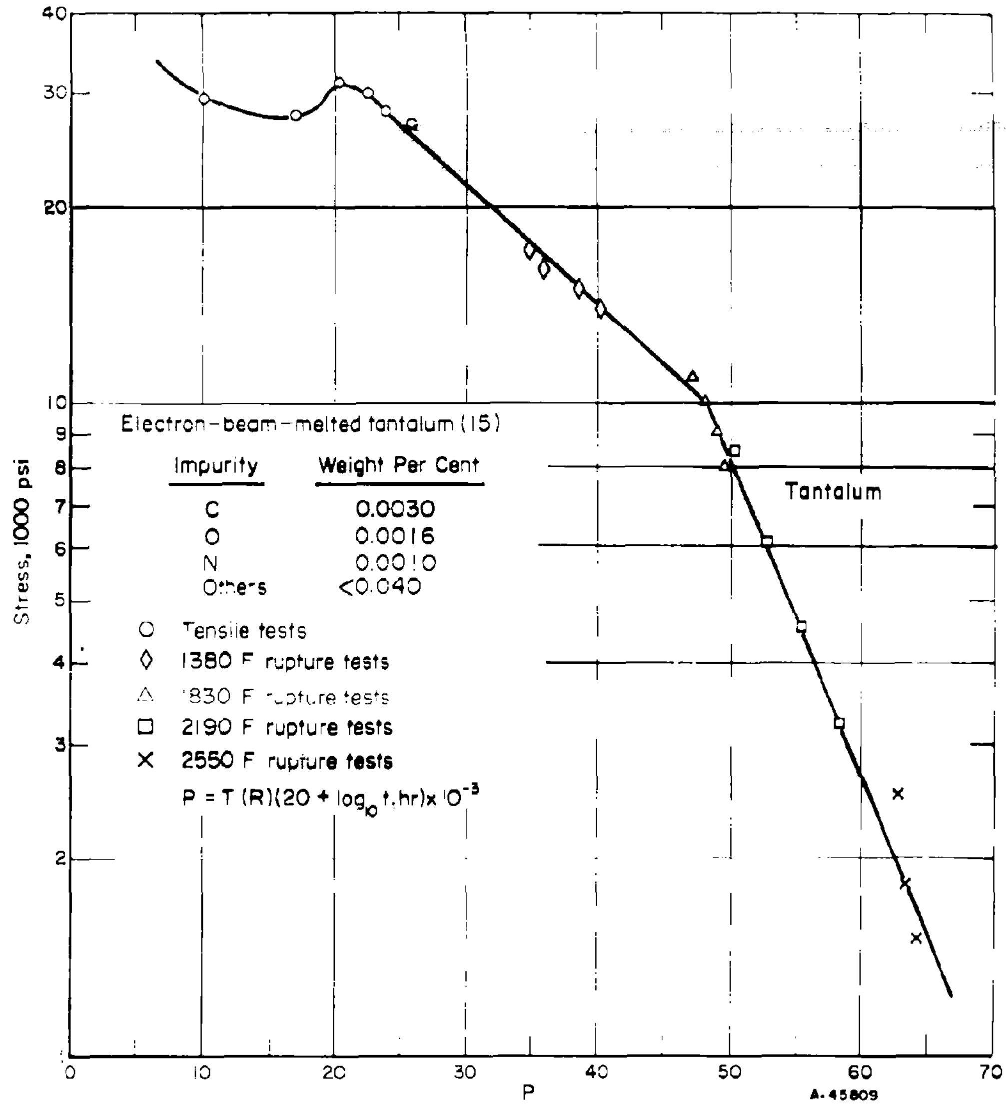


FIGURE A-18. LARSON-MILLER PLOT COMPARING RUPTURE PROPERTIES OF ELECTRON-BEAM-MELTED **TANTALUM SHEET (0.040 INCH)**(15)

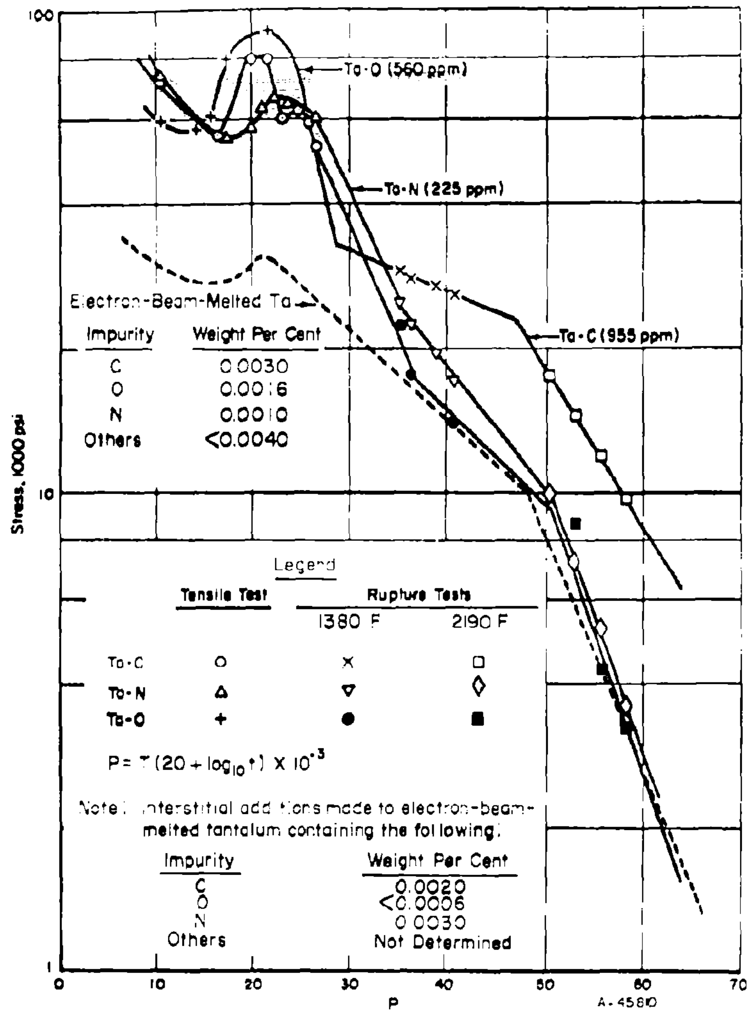


FIGURE A-20. LARSON-MILLER PLOT COMPARING RUPTURE PROPERTIES OF RECRYSTALLIZED ELECTRON-BEAM-MELTED TANTALUM, Ta-C, Ta-N, AND Ta-O ALLOYS IN SHEET (0.040 INCH) FORM[15]

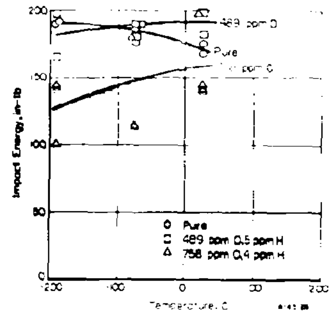


FIGURE A-21. EFFECT OF OXYGEN CONTENT ON THE IMPACT PROPERTIES OF WROUGHT ELECTRON-BEAM-MELTED TANTALUM(23)

Starting material contained <44 ppm combined carbon and nitrogen.

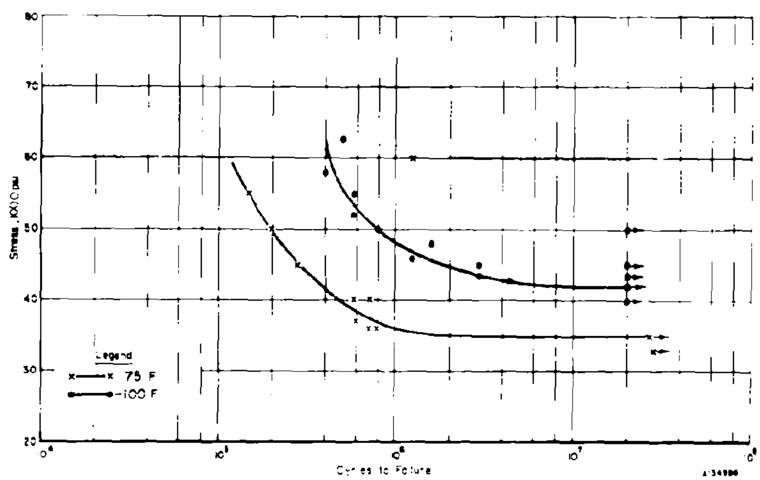
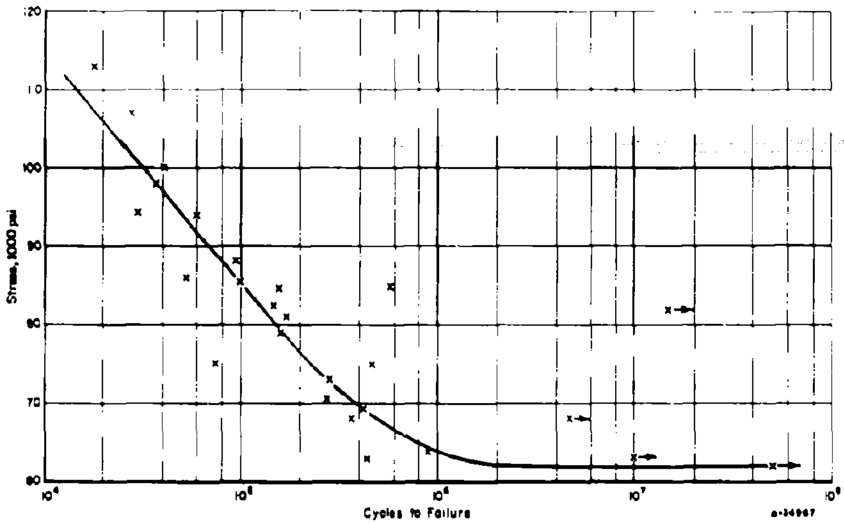
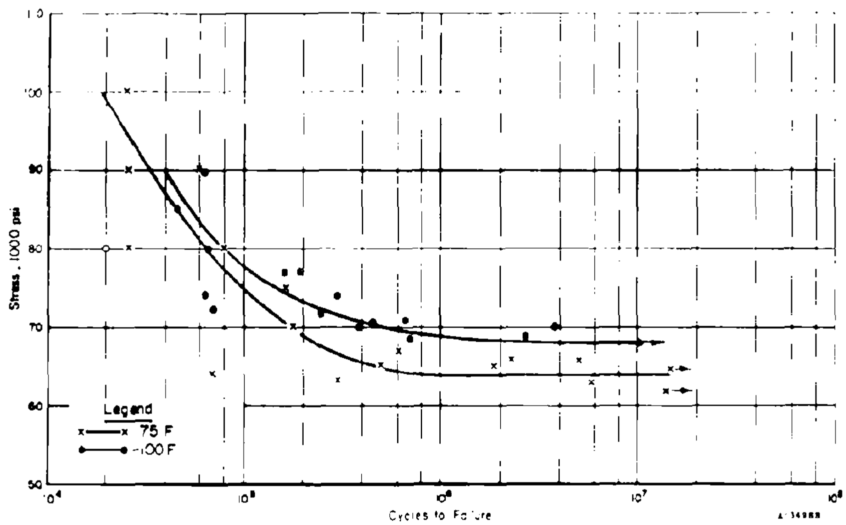


FIGURE A-22. EFFECT OF OXYGEN CONTENT ON THE IMPACT PROPERTIES OF WROUGHT ELECTRON-BEAM-MELTED TANTALUM(23)

Starting material contained <44 ppm combined carbon and nitrogen.



a. Annealed 1 Hour at 2085 F



b. Annealed 1 Hour at 2550 F

FIGURE A-23. FATIGUE CHARACTERISTICS OF ANNEALED TANTALUM WIRE (0.004 INCH)(18)

4. Metallurgical Properties

a. Fabricability: possesses excellent room-temperature fabrication characteristics amenable to all conventional fabrication practices and can be fabricated to large reductions (>95 per cent) without the need for process annealing[3]

b. Transition temperature: <-420 F[21]

c. Weldability: can be welded using conventional techniques wherein, air is excluded, such as inert-gas-shielded tungsten-arc welding, inert-atmosphere chamber, electron-beam welding, and resistance spot or seam welding[7]

d. Stress-relief temperature: 1 hour at 1800 F[24]

e. Recrystallization temperature: Tables A-14 and A-15
Figures A-24 through A-26

TABLE A-14. RECRYSTALLIZATION BEHAVIOR OF ELECTRON-BEAM-MELTED TANTALUM SHEET (0.040 INCH)[a][15]

Condition	Temperature, F, for Indicated Amount of Recrystallization in 1 Hour	
	50 Per Cent	100 Per Cent
Cold reduced 50 per cent from as-cast ingot	2010	2550
Cold reduced 75 per cent from as-cast ingot	1830	2190
Cold reduced 95 per cent from as-cast ingot	[illegible]	2370
Cold reduced 75 per cent after intermediate annealing	1920	2190

(a)

Impurity	Weight Per Cent
C	0.0030
O	0.0016
N	0.0010
Others	<0.040

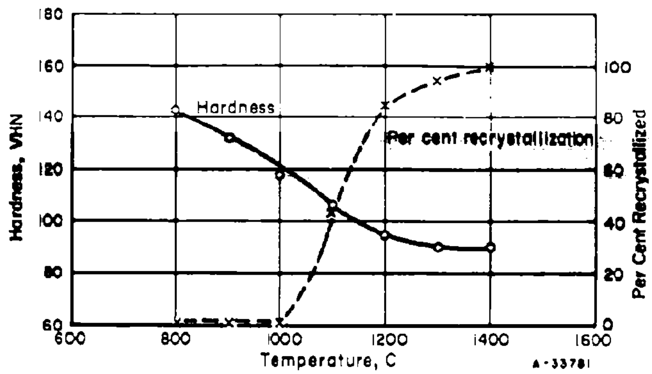


FIGURE A-24. ANNEALING CURVE FOR ELECTRON-BEAM-MELTED TANTALUM BAR[21]

1/4 hour at temperature, furnace cooled.

Electron-beam-melted ingot cold forged and swaged 87 per cent.

Element	Weight Per Cent
C	<0.003
O	<0.003
N	0.0008
Others	<0.08

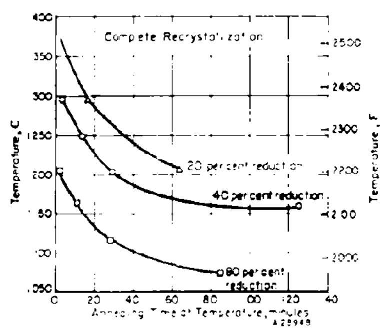


FIGURE A-25. EFFECT OF ANNEALING TIME AND REDUCTION ON THE RECRYSTALLIZATION BEHAVIOR OF TANTALUM[25]

TABLE A-15. GRAIN SIZE VERSUS ANNEALING TEMPERATURE FOR ELECTRON-BEAM-MELTED TANTALUM SHEET (0.040 INCH)[a] (25)

1-Hour Annealing Temperature, F	Average ASTM Grain Size at 100X
2100	5-6
2370	4
2550	3-4
2595	3-4
2910	2
3090	1
3270	0-1

(a) Cold rolled 75 per cent.

Impurity	Weight Per Cent
C	0.0030
O	0.0010
N	0.0010
Others	<0.040

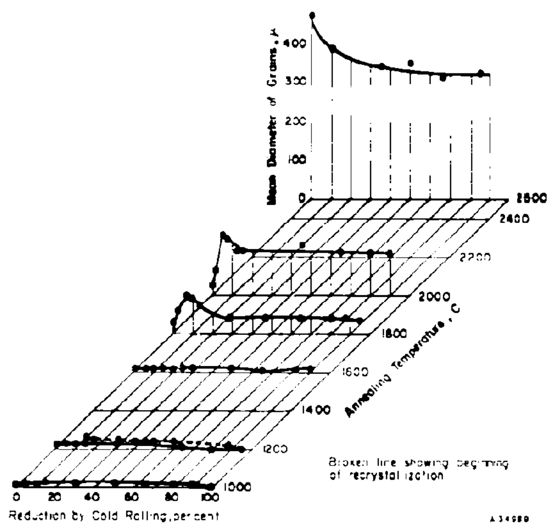


FIGURE A-26. ANNEALING TEMPERATURE VERSUS COLD REDUCTION AND GRAIN SIZE (26)

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(2) Tentative Specifications for Tantalum Rod and Wire, American Society for Testing and Materials, ASTM Designation: B 365-62T (Issued, 1961; Revised, 1962).

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(24) Unpublished data, Battelle Memorial Institute (1959-1961).

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Ta-10W

1. Identification of Material

   a. Designation: several, depending upon individual supplier

   b. Chemical composition: Tables A-16 and A-17

   c. Forms available: ingot, billet, bar, plate, sheet, strip, foil, rod, and wire[1,2]

TABLE A-16. CHEMICAL REQUIREMENTS FOR ARC-CAST AND ELECTRON-BEAM CAST Ta-10W[(a)(1,2)]

Element	Impurity Content[(b)], Maximum, weight per cent
O	0.010
N	0.005
C	0.005
Cb	0.10
Fe	0.01
Mo	0.10
Ni	0.005
Si	0.015
Ti	0.01
W	9-11

(a) For ingot, billet, bar, plate, sheet, strip, foil, rod, and wire.
(b) Any other one impurity to be less than 100 ppm.

TABLE A-17. REPRESENTATIVE ANALYSES OF Ta-10W AS PRODUCED BY ARC MELTING AND ELECTRON-BEAM MELTING PROCESSES

Element	Impurity Content, ppm, for Ingot, Made by						
	Arc Melting				Electron-Beam Melting		
	Ref. (3)	Ref. (4)	Ref. (5)	Ref. (6)[(a)]	Ref. (3), Top	Ref. (3), Bottom	Ref. (6)[(b)]
Al	<20	--	--	--	<20	<20	--
B	<1	--	--	--	<1	<1	--
C	<30	19	15	17	<30	<30	11
Cb	<100	--	--	--	980	1500	--
Cd	<5	--	--	--	<5	<5	--
Cr	<20	5	10	<10	<20	<20	<10
Cu	<40	--	--	--	<40	<40	--
Fe	<100	15	50	<10	<100	<100	<10
H	4	--	--	--	--	--	--
Hf	<80	--	--	--	--	--	--
Mg	<20	--	--	--	<20	<20	--
Mn	<20	--	--	--	<20	<20	--
Mo	<20	<10	25	--	50	250	--
N	11	19	25	36	28	20	35
Ni	<20	5	50	<10	<20	<20	<10
O	140	18	110	52	50	60	22
Pb	<20	--	--	--	<20	<20	--
Si	<100	--	25	--	<100	<100	--
Sn	<20	--	--	--	<20	<20	--
Ta	Bal	Bal	--	--	Bal	Bal	--
Ti	<150	--	10	--	<150	<150	--
V	<20	--	--	--	<20	<20	--
W	10.0%	9.8%	--	--	9.0%	8.6%	--
Zn	<20	--	--	--	<20	<20	--
Zr	<500	--	--	--	<500	<500	--

(a) Starting stock 150 to 450 ppm oxygen. Average values from 14 double-arc-melted ingots.
(b) Starting stock 150 to 450 ppm oxygen. Average values from 7 electron-beam-melted ingots.

2. Physical Properties

   a. Melting point: 5495 F[7]

   b. Density: 0.608 lb/in.^{3}[7]

   c. **Thermal expansion: Table A-18**
      Figures A-27 and A-28

   d. **Thermal conductivity: Table A-19**

TABLE A-18. THERMAL EXPANSION OF Ta-10W[8]

Temperature, F	$\Delta L/L$[a]
1830	0,0054
2010	0,0062
2190	0,0070
2370	0,0079
2550	0,0088
2730	0,0098
2910	0,0107
3090	0,0117
[illegible]	[illegible]
3450	0,0138
3630	0,0148
3810	0,0160
[illegible]	[illegible]
4170	0,0182
4350	0,0192
4530	0,0200
4710	0,0207
4980	0,0213
5070	0,0218
5250	0,0222

(a) From room temperature to indicated temperature.

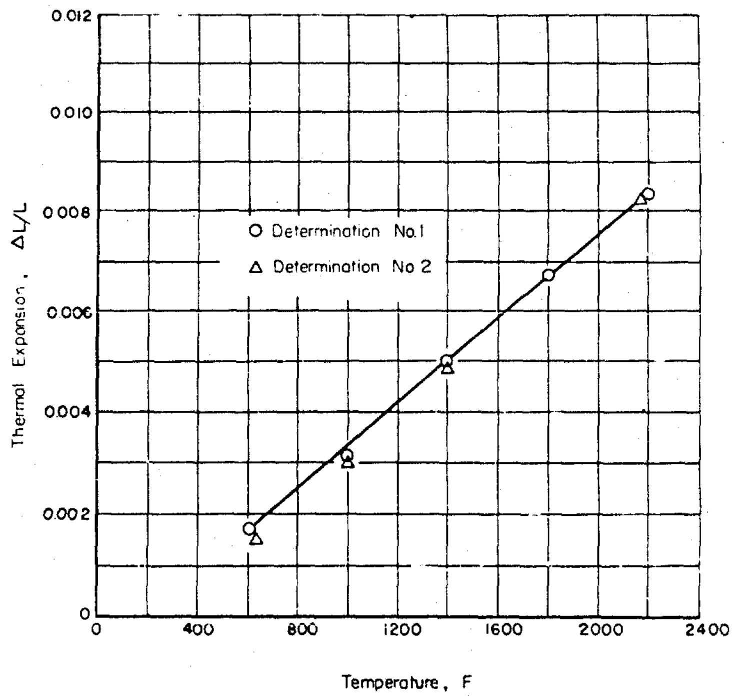

FIGURE A-27. THERMAL EXPANSION OF Ta-10W(9)

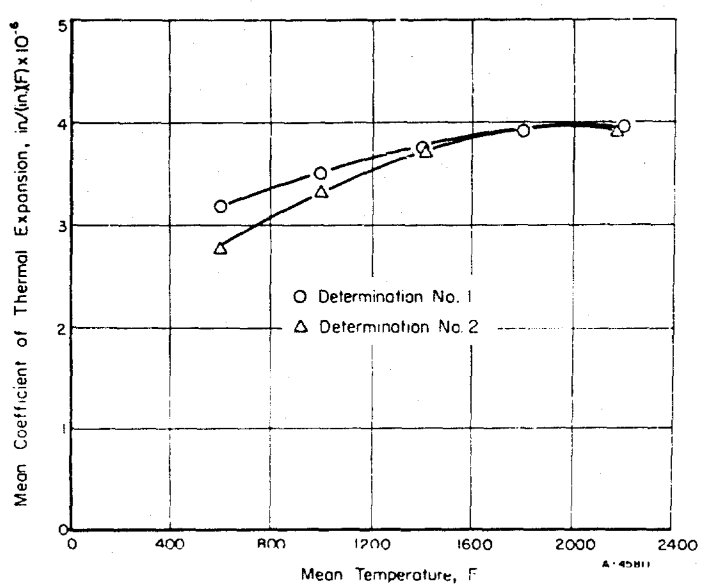

FIGURE A-28. MEAN COEFFICIENT OF THERMAL EXPANSION OF Ta-10W(9)

TABLE A-19. THERMAL CONDUCTIVITY OF Ta-10W[8]

Temperature, K	Thermal Conductivity, cal/(cm^2)(sec)(K/cm)
1700	0.135
1800	0.131
1900	0.128
2000	0.124
2100	0.121
2200	0.117
2300	0.114
2400	0.110
2500	0.107
2600	[illegible]
2700	0.100
2800	0.096
2900	0.092
3000	0.089
3100	0.085
3200	0.082

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-20 through A-22
Figure A-29

Tensile yield strength: Tables A-20 through A-22
Figure A-29

Elongation: Tables A-20 through A-22
Figure A-30

Reduction in area: Table A-22

Modulus of elasticity: $28\text{-}30 \times 10^6$ psi(4)

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-23 through A-26
Figures A-31 through A-34

Tensile yield strength: Tables A-23 through A-26
Figures A-32 and A-34

Elongation: Tables A-23 through A-26
Figures A-32 and A-35

Modulus of elasticity: Tables A-25 and A-26
Figure A-31

c. Notched Tensile Properties

Figures A-36 and A-37

d. Creep and Stress-Rupture Properties

Tables A-27 through A-30
Figures A-38 through A-39

e. Other Selected Mechanical Properties

Hardness: Figure A-40

Impact: Figure A-41

Fatigue: Figure A-42

TABLE A-20. TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST AND ELECTRON-BEAM-CAST Ta-10W FLAT MILL PRODUCTS[a][1]

Condition	Tensile Strength, 1000 psi Min	Tensile Strength, 1000 psi Max	Yield Strength (0.2% Offset), 1000 psi Min	Yield Strength (0.2% Offset), 1000 psi Max	Elongation in 2 Inches, per cent: Specimens 0.021 - 0.1875 In. Thick	Elongation in 2 Inches, per cent: Specimens 0.005 - 0.020 In. Thick
As rolled	150	190	140	180	--	--
Stress relieved	90	130	80	120	5	3
Recrystallization annealed	70	100	60	90	20	15

(a) For bar, plate, sheet, strip, and foil. Tensile properties shall be determined using a strain rate of 0.005 inch per inch per minute through 0.6 per cent offset, and 0.02 to 0.05 inch per inch per minute to fracture.

TABLE A-21. TENSILE-PROPERTY REQUIREMENTS FOR ARC-CAST AND ELECTRON-BEAM-CAST Ta-10W ROD AND WIRE[a][2]

Condition	Tensile Strength, 1000 psi Min	Tensile Strength, 1000 psi Max	Yield Strength (0.2% Offset), 1000 psi Min	Yield Strength (0.2% Offset), 1000 psi Max	Elongation, per cent: In 2 In. (Rod)	Elongation, per cent: In 10 In. (Wire)
As worked	150	190	140	180	--	--
Stress relieved	[illegible]	130	-	[illegible]	[illegible]	5
Recrystallization annealed	70	100	60	90	10	10

(a) Tensile properties shall be determined using a strain rate of 0.02 inch per inch per minute.

TABLE A-22. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF Ta-10W

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
Annealed sheet (2200 F, 0.028 inch)(a)	123.3	114.1	13	--	10
Annealed sheet (2600 F, 0.028 inch)(a)	96.0	82.2	26	--	10
Stress-relieved sheet (3 hr 2250 F, 0.040 inch)(b)	109.1(L) 112.9(T)	101.1(L) 112.9(T)	15.8(L) 14.7(T)	-- --	4 4
Cold-worked sheet (95%, 0.060 inch)	180.0	164.0	4	--	11
Recrystallized sheet (0.060 inch)	90.0	83.5	28.5	--	11
Annealed sheet (0.020-0.250)(c)	70.0(min)	60.0(min)	15(min)	--	12
Annealed sheet(d)	80.0	67.0	25	--	7
Cold-rolled sheet (50%)(d)	147.0	146.5	3	--	7
Cold-rolled sheet (90%)(d)	160.0	--	1	--	7
Stress-relieved rod (rolled 83%, 1 hr 2190 F, 0.125 inch)(e)	134.8	125.9	31	83.2	5
Recrystallized rod (rolled 83%, 1 hr 2730 F, 0.125 inch)(e)	90.1	76.5	35	59.0	5
Annealed bar (2200 F, 1/4 inch)(a)	106.4	99.6	24	--	10
Annealed bar (2600 F, 1/4 inch)(a)	84.2	70.6	34	--	10

(a) Average of two values. Test rate 0.005 inch per inch per minute to 0.2 per cent yield, 0.02 inch per inch per minute to failure. Typical analyses 0.0080% C, 0.0040% O, 0.0100% N, and 0.0005% H.

(b) Arc Melted. Test rate 0.005 inch per inch per minute to 0.6 per cent offset, and 0.05 inch per inch per minute to fracture. Analyses 9.8% W, 0.0019% C, 0.0018% O, 0.0019% N, 0.0015% Fe, 0.0005% Cr, 0.0005% Ni, and <0.0010% Mo.

(c) Test rate 0.005 inch per inch per minute to 0.6 per cent offset, and 0.02 to 0.05 inch per inch per minute to fracture. Composition shall conform to the following maximums 0.0050% C, 0.0070% O, 0.0030% N, 0.0006% H, 0.10% Cb, 0.0070% Fe, 0.0300% Mo, 0.0070% Ni, and have a tungsten range of 8.5 to 11 per cent.

(d) Electron-Beam Melted. Typical analyses 9-11% W, 0.0060% O, 0.0030% N, <0.0010% H, 0.0020% C, 0.050% Cb, and others 0.020%.

(e) Arc Melted. Average of two values. Crosshead speed 0.02 inch per minute. Analyses 0.0015% C, 0.0010% Cr, [illegible]% Fe, 0.0025% Mo, 0.0025% N, 0.0050% Ni, 0.0110% Ni, 0.0025% Si, and 0.0010% Ti.

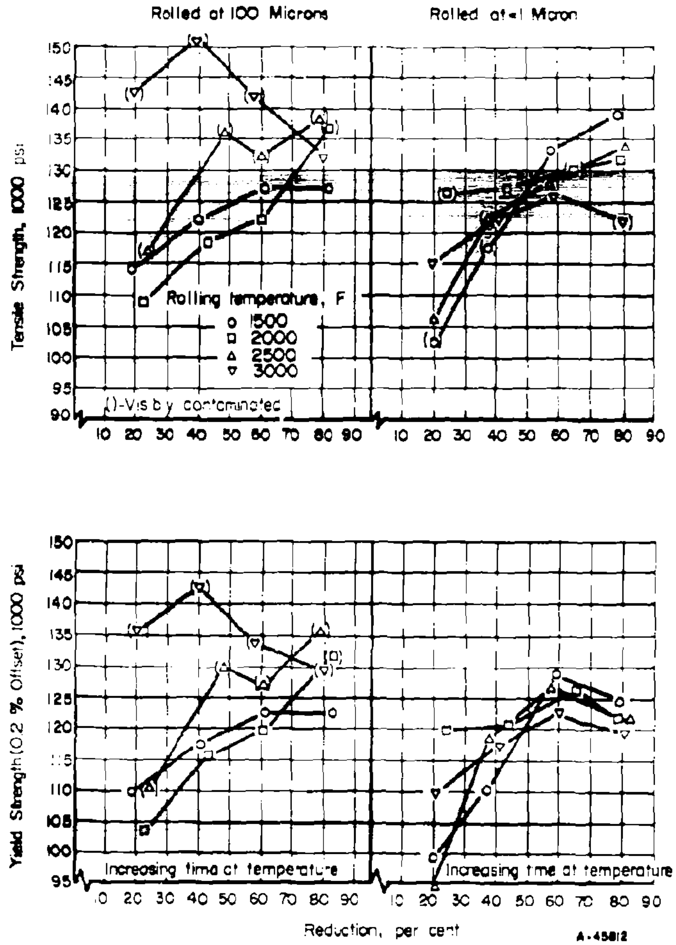

FIGURE A-29. EFFECT OF ROLLING TEMPERATURE, CHAMBER PRESSURE, AND PER CENT DEFORMATION ON THE ROOM-TEMPERATURE STRENGTH OF AS-ROLLED Ta-10W SHEET(13)

Tested at 0.005 inch per inch per minute.

Impurity	PPM
C	12-26
O	12-36
N	22-44
H	1.9-2.5

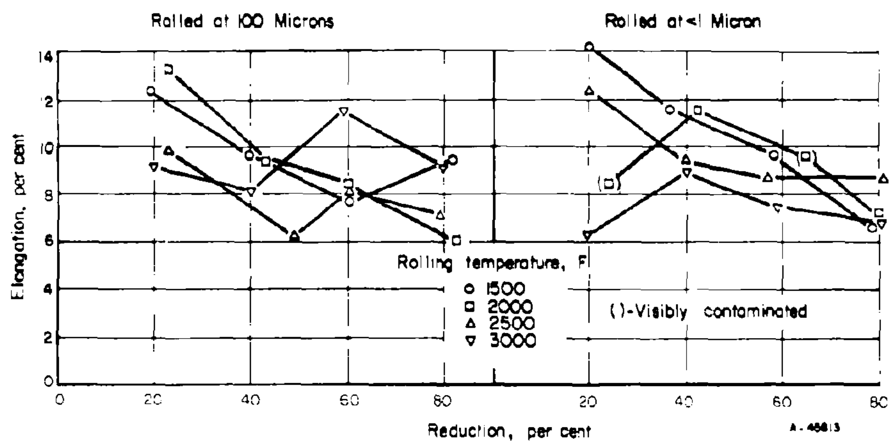

FIGURE A-30. EFFECT OF ROLLING TEMPERATURE, CHAMBER PRESSURE, AND PER CENT DEFORMATION ON THE ROOM-TEMPERATURE TENSILE DUCTILITY OF AS-ROLLED Ta-10W SHEET(13)

Tested at 0.005 inch per inch per minute.

Impurity	PPM
C	12-26
O	12-36
N	22-44
H	1.9-2.5

TABLE A-23. TENSILE PROPERTIES OF ANNEALED Ta-10W SHEET AND BAR AT 2200 F(a)(10)

Form	Annealing Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
Sheet, 0.028 inch	2200	58.8	33.7	11
	2600	37.1	22.3	36
Bar, 3/8 inch	2200	38.3	34.1	13
	2600	36.2	26.3	30

(a) Average of two values. Test rate 0.005 inch per inch per minute to 0.2 per cent yield, and 0.02 inch per inch per minute to failure. Typical analyses 0.0080% C, 0.0040% O, 0.0100% N, and 0.0005% H.

TABLE A-24. TENSILE PROPERTIES OF ARC-CAST STRESS-RELIEVED Ta-10W SHEET (0.040 INCH) AT 2000 TO 3000 F(a)(4)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
2000	60.7	55.1	11
2400	39.5	34.7	19
3000	19.2	16.4	84

(a) Stress relieved for 3 hours at 2250 F. Tested at 0.05 inch per inch per minute. Analyses 9.8% W, 0.0019% C, 0.0018% O, 0.0010% N, 0.0015% Fe, 0.0005% Cr, 0.0005% Ni, and <0.0010% Mo.

TABLE A-26. TENSILE PROPERTIES OF ARC-CAST STRESS-RELIEVED Ta-10W SHEET[a][14]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Modulus of Elasticity, 10^6 psi
RT	165.0	165.0	1.3	25.0
	164.0	162.0	3.3	25.3
	166.0	160.0	3.3	24.0
500	138.1	137.0	0.8	24.0
	143.0	140.0	2.0	23.0
1000	131.0	128.0	0.9	21.8
	132.0	129.0	1.3	20.8
1500	104.0	96.3	2.7	19.0
	104.0	96.4	3.3	18.0
2000	77.9	64.4	6.7	15.6
	77.8	64.7	7.3	15.1
	75.1	62.9	7.3	15.1
2500	50.5	39.0	6.4	10.6
	53.5	40.2	8.3	9.4
	61.4	48.5	8.7	10.5
	[illegible]	[illegible]	7.0	10.5
3000	19.0	13.0	33.4	5.5
	20.2	14.2	33.0	5.2
	21.5	15.1	20.0	5.0

(a) Test Conditions:

Atmosphere	Argon
Gage Length	1.5 in.
Sheet Thickness	0.040 in.
Analyses	0.0051% O, <0.0001% H, 0.0015% N, 0.0014% C, 0.0012% Fe, 0.0010% Cr, and 0.0010% Ni
Method of Heating	Resistance
Time to Temperature	200 F/sec
Hold at Temperature	5 minutes
Strain Rates	0.001 in./in./sec to yield 0.01 in./in./sec to fracture

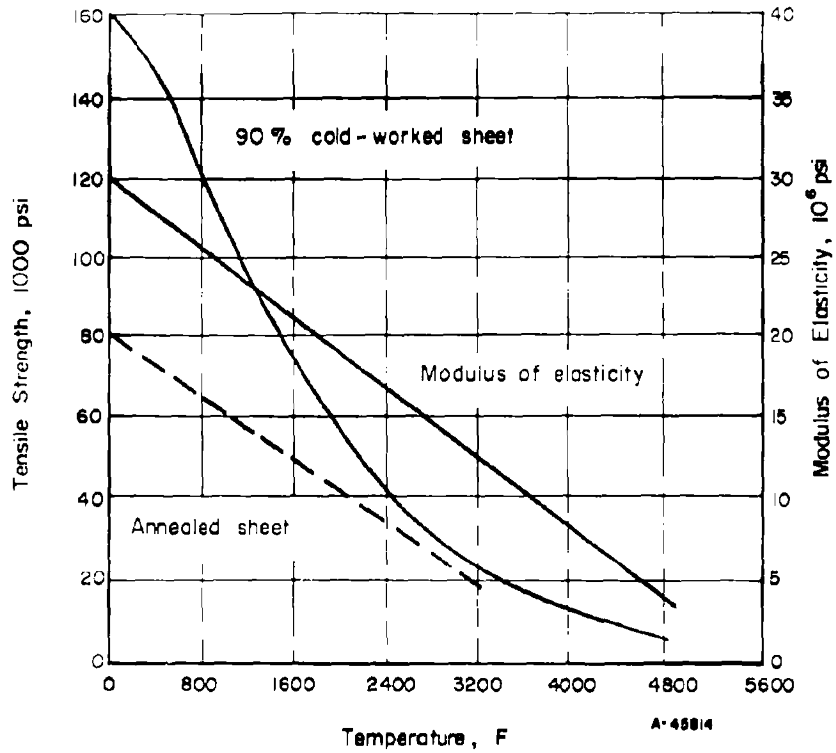

FIGURE A-31. TYPICAL ELEVATED-TEMPERATURE TENSILE PROPERTIES OF ELECTRON-BEAM-MELTED Ta-10W SHEET[7]

Typical analyses:

Impurity	Weight Per Cent
W	9-11
O	0.0060
N	0.0030
H	<0.0010
C	0.0020
Cb	0.050
Others	0.0200

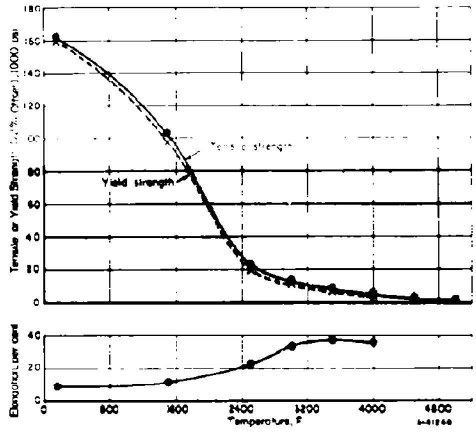

FIGURE A-32. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF WROUGHT ARC-CAST Ta-10W SHEET (0.060 INCH)(15)

Approximate strain rate of 0.01 inch per inch per minute. Total interstitial content approximately 0.0070 per cent. Tested in argon.

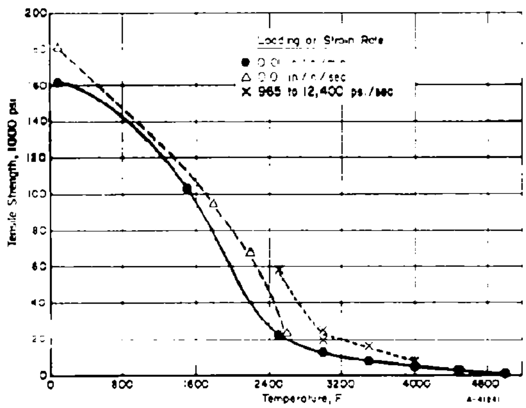

FIGURE A-33. EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE STRENGTH OF WROUGHT ARC-CAST Ta-10W SHEET (0.060 INCH)(15)

Total interstitial content approximately 0.0070 per cent. Tested in argon.

TABLE A-26. TENSILE PROPERTIES OF Ta-10W AT 2500 TO 4500 F USING RAPID LOADING RATES[a][15]

Temperature, F	Loading Rate, psi/sec	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Modulus of Elasticity, 10^6 psi
2500	12,400	63.4	--	3.0	5.3
		59.2	44.0	3.3	8.5
		51.4	44.0	11.0	6.1
3000	4,500	24.7	17.7	7.4	5.8
		25.8	14.3	15.0	3.6
		25.6	13.3	16.9	2.0
3500	1,960	17.1	12.4	21.2	1.22
		15.4	12.75	25.6	1.35
		15.6	8.8	26.0	1.39
4500	1,930	8.6	3.6	16.8	0.19
		6.3	--	21.2	--
		7.7	3.5	11.9	0.19

(a) Annealed 0.050-inch sheet tested in argon.

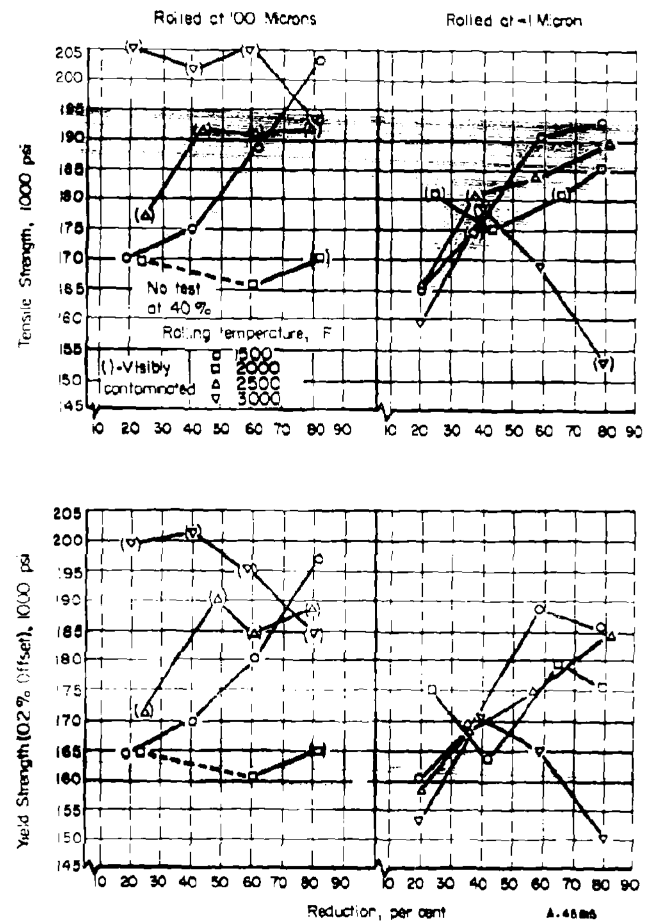

FIGURE A-34. EFFECT OF ROLLING TEMPERATURE, CHAMBER PRESSURE, AND PER CENT DEFORMATION ON THE -300 F TENSILE STRENGTH OF AS-ROLLED Ta-10W SHEET(13)

Tested at 0.005 inch per inch per minute.

Impurity	PPM
C	12-26
O	12-36
N	22-44
H	1.9-2.5

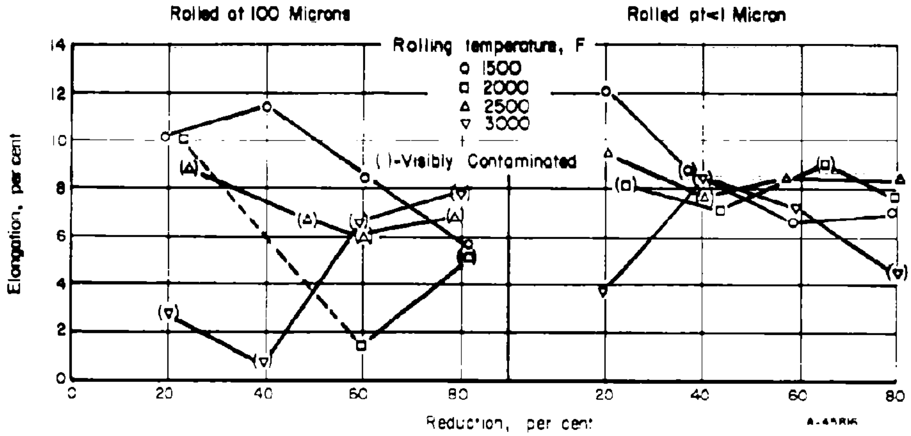

FIGURE A-35. EFFECT OF ROLLING TEMPERATURE, CHAMBER PRESSURE, AND PER CENT DEFORMATION ON THE -300 F TENSILE DUCTILITY OF AS-ROLLED Ta-10W SHEET(13)

Tested at 0.005 inch per inch per minute.

Impurity	PPM
C	12-26
O	12-36
N	22-44
H	1.9-2.5

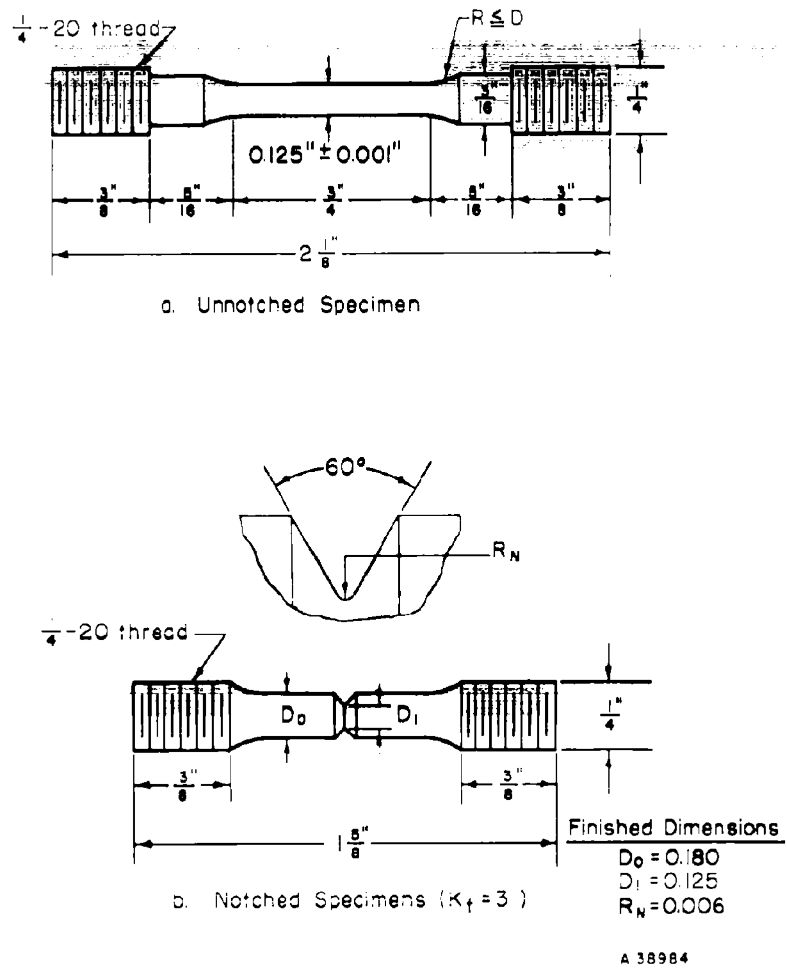

FIGURE A-36. UNNOTCHED AND NOTCHED-BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURE A-37

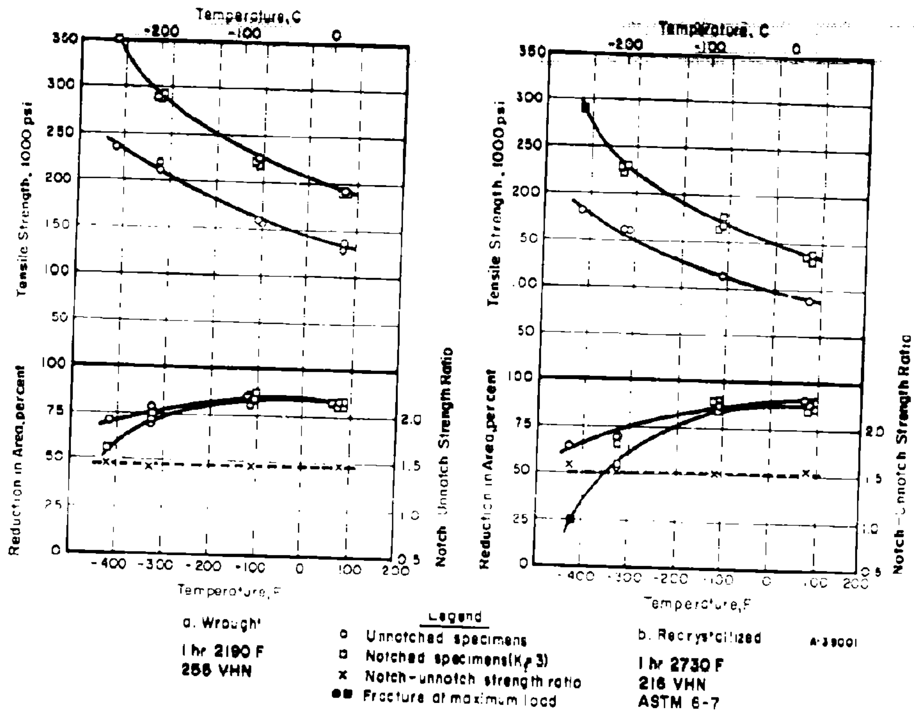

FIGURE A-37. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ARC-MELTED Ta-10W BAR(5)

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Impurity	Weight Per Cent
C	0.0015
O	0.0110
N	0.0025
Others	0.0170

TABLE A-27. STRESS-RUPTURE CHARACTERISTICS OF ARC-CAST Ta-10W SHEET (0.040 INCH)

Temperature, F	Condition	Stress, 1000 psi	Time to Rupture, hours	Reference
[illegible]	Stress relieved[a]	53.0	1.5	(4)
		50.0	2.4	
		47.0	6.8	
		45.0	20.0	
2400	Stress relieved[a]	38.0	0.1	(4)
		28.0	2.8	
		25.0	4.0	
		22.0	16.4	
2700	Recrystallized[b]	19.0	1.93	(17)
		16.5	4.83	
3500	Recrystallized[b]	8.0	0.53	(17)
		5.6	3.4	

(a) 3 hours at 2250 F. Analyses 9.8% W, 0.0019% C, 0.0018% O, 0.0019% N, 0.0015% Fe, 0.0005% Cr, 0.0005% Ni, and <0.0010% Mo.

(b) 1 hour at 2730 F. Data obtained from small button-type ingots.

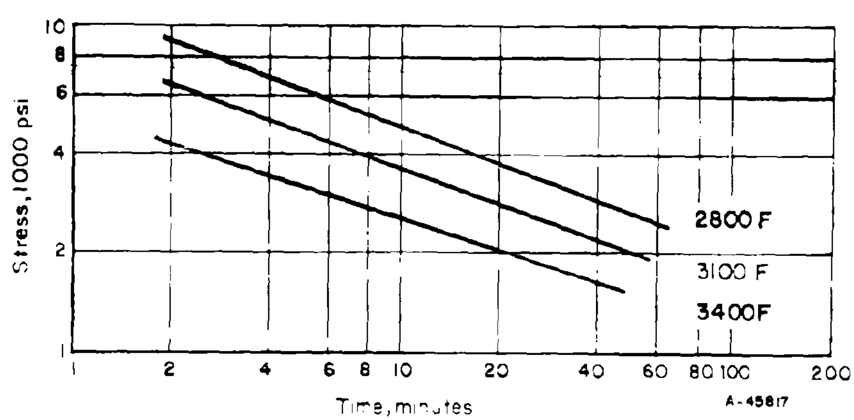

FIGURE A-38. TIME FOR 0.2 PER CENT CREEP AT VARIOUS STRESS LEVELS FOR Ta-10W[16]

TABLE A-28. CREEP-RUPTURE PROPERTIES FOR ELECTRON-BEAM-MELTED STRESS-RELIEVED Ta-10W SHEET(a)(14)

Temp, F	Stress, 1000 psi	Approx. Thermal Exp., in.	Loading Strain, per cent	Time, sec, to Produce Indicated Plastic Creep 0.05%	0.2%	0.5%	1.0%	2.0%	4.0%	6.0%	8.0%	10.0%	Time to Rupture, sec	Elong., per cent
2000	65	0.0105	0.53	0.6	7.1	30	67	95	--	--	--	--	99	3.3
2000	60	0.0105	0.27	8.0	36	121	470	770	--	--	--	--	772	8.3
2500	50	0.0138	0.27	--	0.6	2.0	4.8	13	45	60	--	--	67	14.0
2500	45	0.0138	0.27	0.1	0.3	3.0	8.0	22	78	101	114	--	119	19.3
2500	40	0.0138	0.30	0.1	2.0	11.0	28	44	80	199	--	--	210	14.6
3000	18	0.0162	0.53	--	0.4	1.0	2.4	5.1	13	38	58	81	250	38.6
3000	16	0.0162	0.23	7.0	60	137	258	525	975	1387	1740	2140	--	21.3
3500	8	0.0193	0.07	3.1	8.5	28	53	97	172	232	280	325	466	30.0
3500	6	0.0193	0.02	31	165	305	501	815	1370	1760	1980	2150	2550	30.0
4000	6	0.0240	0.07	0.1	1.6	3.3	6.0	11	21	26	31	35	49	30.0
4000	4	0.0240	--	5.5	52	130	225	--	--		--	--	349	(b)

(a) Test Conditions:

Atmosphere	Argon
Gage Length	1.5 in.
Sheet Thickness	0.040 in.
Analyses	0.0206% O, <0.0001% H, and 0.0005% N
Method of Heating	Resistance

(b) Specimen failed in radius.

TABLE A-29. CREEP-RUPTURE PROPERTIES FOR ARC-CAST STRESS-RELIEVED Ta-10W SHEET AT 2000 F(a)(14)

Stress, 1000 psi	Approx. Thermal Exp., in.	Loading Strain, per cent	Time, sec, to Produce Indicated Plastic Creep 0.05%	0.2%	0.5%	1%	2%	4%	Time to Rupture, sec	Elong., per cent
70	0.0105	0.4	--	0.4	1.4	2.7	6.5	12	14	7.3
65	0.0105	0.47	0.4	2.5	9.5	21	46	74	84	7.3
65	0.0105	0.46	1.8	9.0	32	98	148	270	280	6.7
60	0.0105	0.33	0.1	0.5	2.8	10	27	45	49	6.7
60	0.0105	0.39	2.0	12	34	82	174	328	332	8.0
55	0.0105	0.27	3.0	32	140	415	841	1746	1749	5.3
50	0.0105	0.25	10	80	235	945	2940	--	3685	3.3

(a) Test Conditions:

Atmosphere	Argon
Gage Length	1.5 in.
Sheet Thickness	0.040 in.
Analyses	0.0051% O, <0.0001% H, 0.0015% N, 0.0014% C, 0.0012% Fe, 0.0010% Cr, and 0.0010% Ni
Method of Heating	Resistance

TABLE A-30. CREEP-RUPTURE PROPERTIES FOR ARC-CAST STRESS-RELIEVED Ta-10W SHEET[(a)(14)]

Stress, 1000 psi	Approx. Thermal Exp., in.	Loading Strain, per cent	Time, sec, to Produce Indicated Plastic Creep 0.05%	0.2%	0.5%	1%	2%	4%	6%	8%	10%	Time to Rupture, sec	Elong., per cent
						At 2500 F							
55	0.0138	0.35	--	--	0.9	1.5	2.6	3.0	4.0	--	--	5.0	8.7
50	0.0138	--	--	--	--	--	--	--	--	--	--	3.2	18.7
50	0.0138	--	--	--	--	--	--		--	--	--	2.0	8.0
45	0.0138	0.27	0.5	3.0	10	31	68	166	185	--	--	187	12.7
45	0.0138	0.27	--	0.2	1.2	3.0	5.0	10	11	--	--	13	8.0
40	0.0138	0.3	0.1	1.2	3.0	8.5	18	36	39	--	--	43	10.0
35	0.0138	0.26	0.1	3.4	15	35	76	134	170	179	--	183	12.0
						At 3000 F							
20	0.0162	--	--	--	--	--	--	--	--	--	--	14	33.3
18	0.0162	--	--	--	--	--	--	--	--	--	--	43	37.4
18	0.0162	--	--	--	--	--	--	--	--	--	--	49	36.7
16	0.0162	0.5	1.0	2.0	7.0	25	59	110	161	225	263	522	30.0
16	0.0162	0.67	--	0.9	1.3	2.0	5.0	14	57	87	122	235	36.0
14	0.0162	0.7	--	0.2	1.1	1.9	4.0	19	52	86	107	167	22.6
12	0.0162	0.16	17	45	92	185	344	672	1095	1430	1786	1780+	33.2
						At 3500 F							
10	0.0193	0.54	--	0.4	0.9	2.0	3.5	7.0	12	16	23	76	31.3
8	0.0193	0.07	13	33	51	83	143	242	275	345	393	462	24.0
8	0.0193	0.13	--	--	1.0	5	30	110	185	220	260	405	27.3
6	0.0193	0.07	17	63	145	278	490	871	1145	1280	1395	1663	22.0
4	0.0193	0.03	52	187	440	905	1624	2410	--	--	--	2490	6.0
						At 4000 F							
6	0.024	0.07	--	0.2	1.1	2.0	3.0	6.0	10	13	18	41	30.7
6	0.024	0.13	--	0.3	1.0	1.7	3.2	5.0	7.0	9.0	10	21	26.7
4	0.024	0.03	4.0	35	76	142	--	--	--	--	--	220	(b)
2	0.024	--	57	180	450	--	--		--	--	--	503	(b)

(a) Test Conditions:

Atmosphere	Argon	Analyses	0.0051% O, <0.0001% H, 0.0015% N, 0.0015% C, 0.0012% Fe, 0.0010% Cr, and 0.0010% Ni
Gage Length	1.5 in.		
Sheet Thickness	0.040 in.	Method of Heating	Resistance

(b) Specimen failed in radius.

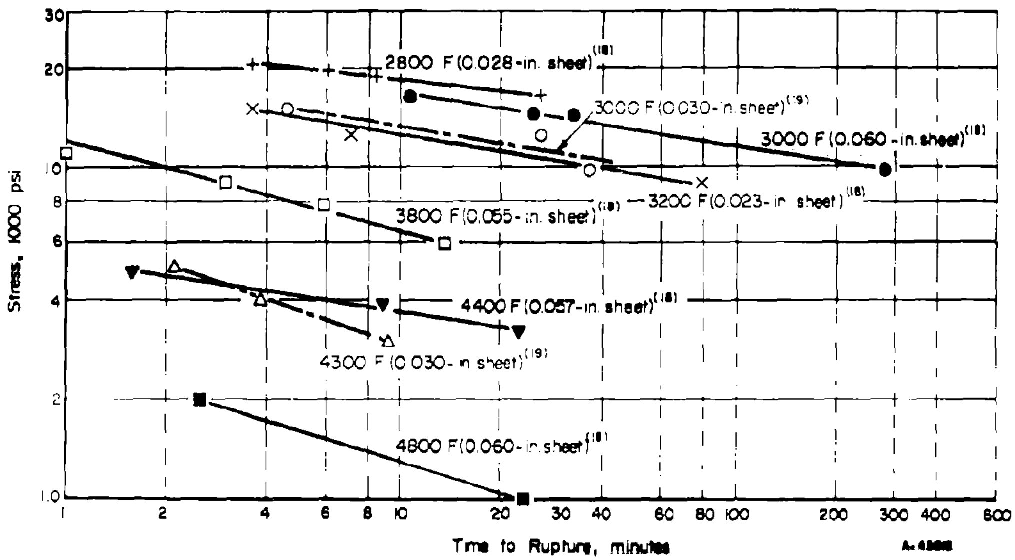

FIGURE A-39. STRESS-RUPTURE STRENGTHS OF WROUGHT (REDUCED >90%) Ta-10W SHEET AT ELEVATED TEMPERATURES

Note: Material from Reference (19).

Analyses 0.0110% O, 0.0015% C, 0.0025% N, 0.0050% Fe, <0.0001% Cr, 0.0050% Ni, <0.0003% Si, <0.0010% Ti, and <0.0003% Mo.

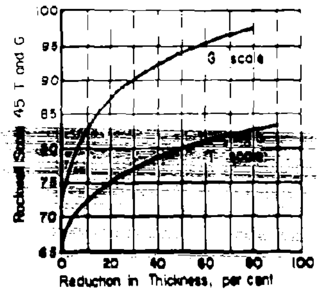

FIGURE A-40. EFFECT OF COLD ROLLING ON THE HARDNESS OF Ta-10W SHEET(7)

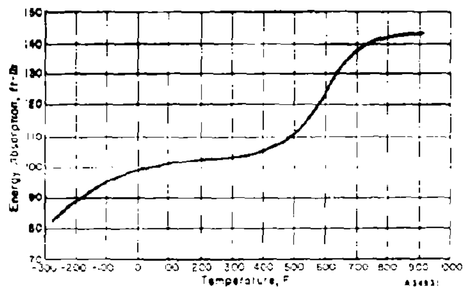

FIGURE A-41. CHARPY-KEYHOLE IMPACT CURVE FOR ELECTRON-BEAM-MELTED Ta-10W(20)

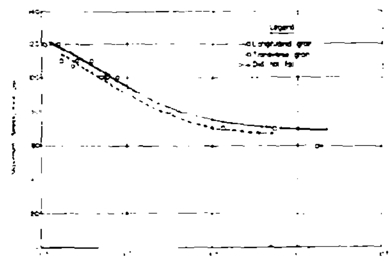

FIGURE A-42. COMPLETELY REVERSED SHEET-BENDING FATIGUE PROPERTIES OF COLD ROLLED Ta-10W SHEET (0.025 INCH) AT ROOM TEMPERATURE(21)

4. Metallurgical Properties

a. Fabricability: forging temperatures range from about 2200 F for breakdown to as low as 1500 F after 50 per cent reduction. It is important to maintain temperatures below 2300 F, to maintain a slightly reducing atmosphere at all times, and to minimize furnace heating time. Open hammer upsetting, piercing, and drawing, as well as closed die forging, may all be satisfactorily accomplished. Breakdown temperatures for annealed sheet bar range from 500 to 700 F, and 80 per cent reductions are possible between anneals. Finish rolling is accomplished at room temperatures, and cold reductions up to 90 per cent may be obtained between anneals.[7]

b. Transition temperature:

	Transition Temp, F[22]	
	Unnotched	Notched
Wrought	<-420	<-420
Recrystallized	<-420	-360

c. Weldability: electron-beam welding or inert-gas fusion welding are used. Stress-relieved or, preferably, fully recrystallized starting material should be used. The properties of properly welded Ta-10W are essentially the same as those of the base metal.[7]

d. Stress-relief temperature: 1 to 3 hours at 2000 to 2250 F[4, 5, 23]

e. Recrystallization temperature: 1 hour at 2400 to 2730 F[4, 5, 7, 23]
Figures A-43 and A-44

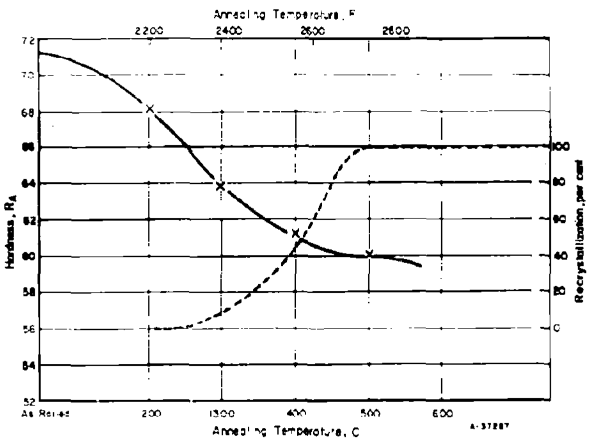

FIGURE A-43. ANNEALING AND HARDNESS CURVES FOR Ta-10W[15]

Double-arc-melted 3-1/2-inch-diameter ingot, forged at 1500 F to 1-inch-thick sheet bar; annealed 1/2 hour at 2730 F, cold rolled to 0.060-inch-thick sheet, 95 per cent reduction in area.

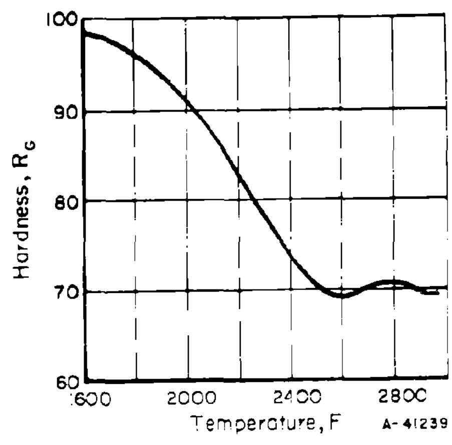

FIGURE A-44. EFFECT OF 15-MINUTE ANNEALING TEMPERATURE ON THE HARDNESS OF 90 PER CENT COLD-ROLLED ELECTRON-BEAM-MELTED Ta-10W SHEET[7]

References

(1) Proposed ASTM Specification For Tantalum 10 Per Cent Tungsten Alloy Flat Mill Products, Second Draft, American Society For Testing and Materials (1963).

(2) Proposed ASTM Specification For Tantalum 10 Per Cent Tungsten Alloy Ingot, Billet, Rod, and Wire, Second Draft, American Society For Testing and Materials (1963).

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(4) National Research Corp., Data Sheet on Ta-10W and Ta-8W-2Hf Alloy Sheet (May 2, 1963).

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(6) Torti, M. L., "Physical Properties and Fabrication Techniques For The Tantalum-10% Tungsten Alloy", paper presented at the AIME Technical Conference on High-Temperature Materials, Cleveland, Ohio (April 26-27, 1961).

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(17) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594, Part II (May, 1963).

(18) Donlevy, A., and Hum, J. K. Y., "Some Stress-Rupture Properties of Columbium, Molybdenum, Tantalum, and Tungsten Metals and Alloys Between 2400-5000 F", paper presented at 1961 SAE National Aeronautic Meeting, New York.

(19) "Tantalum, Tungsten Fill Hot Needs", Chem. and Engr. News, 37 (42), 52 (1959).

(20) Preliminary Information Bulletin on 90 Tantalum-10 Tungsten Alloy, Stauffer-Temescal, Richmond, California (1960).

(21) Foster, L. R., and Stein, B. A., "Tensile Properties and Sheet-Bending Fatigue Properties of Same Refractory Metals at Room Temperature", National Aeronautics and Space Administration, NASA TN D-1592 (January, 1963).

(22) Imgram, A. G., et al., "Low-Temperature Tensile and Notched Tensile Behavior of Mo-0.5Ti, Cb-15W-5Mo-1Zr, and Ta-10W", Battelle Memorial Institute, paper presented at the Fall Meeting of ASM, New York (1962).

(23) Schmidt, F. F., et al., "Investigation of the Properties of Tantalum and Its Alloys", Battelle Memorial Institute, WADD TR 61-106 (March, 1960).

Ta-12.5W

1. Identification of Material

a. Designation: STa-880 (Stauffer)

b. Chemical composition: typical analyses of electron-beam-melted ingot[1]

Element	Weight Per Cent
W	11.5-13.5
O	0.0020
N	0.0020
C	0.0020
H	0.0010
Cb	0.0500
Others	0.0200
Ta	Bal.

c. Forms available: ingot, billet, bar, forgings, plate, sheet, foil, wire, and tubing[1]

2. Physical Properties

a. Melting point: 5520 F (calculated)[1]

b. Density: 0.610 lb/in.^{3} (calculated)[1]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Melting	Condition	Ultimate Tensile Strength (0.040-In. Sheet), 1000 psi: Longitudinal	Ultimate Tensile Strength (0.040-In. Sheet), 1000 psi: Transverse	Reference
Electron beam	Annealed	102.0	102.0	(1)
Arc	1 hour at 2910 F	103.0[a]	--	(2)

(a) Button ingot, 0.05 inch per minute crosshead speed.

Melting	Condition	Tensile Yield Strength (0.2% Offset) (0.040-In. Sheet), 1000 psi Longitudinal	Transverse	Reference
Electron beam	Annealed	85.0	90.0	(1)
Arc	1 hour at 2910 F	95.6[a]	--	(2)

(a) Button ingot, 0.02 inch per minute crosshead speed.

Melting	Condition	Elongation (0.040-In. Sheet), per cent Longitudinal	Transverse	Reference
Electron beam	Annealed	23 (2 in.)	23 (2 in.)	(1)
Arc[a]	1 hour at 2910 F	13 (1 in.)	--	(2)

(a) Button ingot.

b. Effect of Temperature on Tensile Properties

Melting	Condition	Temperature, F	Ultimate Tensile Strength (0.040-In. Sheet), 1000 psi	Reference
Arc	1 hour at 2910 F	2190	50.5[a]	(2)
Arc	1 hour at 2910 F	2700	33.1[a]	(2)
Arc	1 hour at 2910 F	3000	23.0[a]	(2)
Arc	1 hour at 2910 F	3500	13.0[a]	(2)
Electron beam	Annealed	4900	1.860	(1)
Electron beam	Annealed	5300	0.930	(1)

(a) Button ingot, 0.05 inch per minute crosshead speed.

Melting	Condition	Temperature, F	Tensile Yield Strength (0.2% Offset)(0.040-In. Sheet), 1000 psi	Reference
Arc	1 hour at 2910 F	2190	38.0[a]	(2)
Arc	1 hour at 2910 F	2700	23.2[a]	(2)
Arc	1 hour at 2910 F	3000	16.7[a]	(2)
Arc	1 hour at 2910 F	3500	10.0[a]	(2)
Electron beam	Annealed	4900	1.430	(1)
Electron beam	Annealed	5300	0.860	(1)

(a) Button ingot, 0.01 inch per minute crosshead speed.

Melting	Condition	Temperature, F	Elongation (0.040-In. Sheet)[2] in 1 Inch, per cent
Arc[a]	1 hour at 2910 F	2190	18
Arc[a]	1 hour at 2910 F	2700	30
Arc[a]	1 hour at 2910 F	3000	55
Arc[a]	1 hour at 2910 F	3500	52

(a) Button ingot.

c. Other Selected Mechanical Properties

Bend ductility: 0.040-inch sheet, annealed 1 hour at 2910 F[2]

Temperature, F	Minimum Bend Radius, T
75	0
-320	3

4. Metallurgical Properties

a. Fabricability: breakdown temperatures should be above 2000 F. After at least 50 per cent reduction and process annealing, temperatures for final sheet rolling can be reduced to as low as 700 F.[2] Ta-12.5W can be rolled to thin sheet, spun into various shapes, and formed and welded into tubing. Annealed sheet can be spun without difficulty at room temperature.[1]

b. Transition temperature: <-320 F for a 4T minimum bend radius[2]

c. Weldability: sheet can readily be welded by either electron-beam or inert-gas-fusion techniques. As-welded sheet has properties essentially the same as those of the base material;[1,3] however welding increases the transition temperature markedly.[3]

d. Stress-relief temperature: 1 hour at 2000 to 2370 F[2]

e. Recrystallization temperature: 1 hour at 2730 to 2910 F[2]

1-Hour Annealing Temperature, F	Hardness[2], VHN	
	Rolled 45%	Rolled 65%
Cast	260	272
Wrought	345	366
2010	--	[illegible]
2190	306	317
2370	297	317
2550	287	292
2730	276	256[a]
2910	264[a]	251

(a) >75 per cent recrystallized.

References

(1) "STa-880, Ta-12.5W Alloy", Stauffer Metals Division Data Sheet (March, 1963).

(2) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594 (July, 1962).

(3) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594, Part II (May, 1963).

Ta-30Cb-7.5V

1. Identification of Material

   a. Chemical composition: Ta-(28-32)Cb-(5-8)V

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Melting point: 4405 F ± 90 F (for Ta-28.8Cb-7.1V)[1]

   b. Density: 0.425 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-31 and A-32

      Tensile yield strength: Tables A-31 and A-32

      Elongation: Tables A-31 and A-32

      Modulus of elasticity: 21.5-23.5 x 10^6 psi[2]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Figures A-45 and A-46

      Tensile yield strength: Figure A-45

      Elongation: Figure A-45

   c. Other Selected Mechanical Properties

      Bend ductility:

Test Direction	Sheet Thickness, inch	Temperature, F	Minimum Bend Radius, T
	Ta-32Cb-5.1V (1 Hr 2300 F)[2]		
Longitudinal	0.040	75	0
Longitudinal	0.040	-320	0
Transverse	0.040	75	0
Transverse	0.040	-320	0
	Ta-28.8Cb-7.1V (1 Hr 2200 F)[2]		
Longitudinal	0.045	75	0
Longitudinal	0.045	-320	0
Transverse	0.045	75	0
Transverse	0.045	-320	0

TABLE A-31. ROOM-TEMPERATURE TENSILE DATA FOR ARC-CAST Ta-28.8Cb-7.1V SHEET (0.045 INCH)(a)(2)

Test Condition	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
Stress relieved	Longitudinal	154	139	16
(1/2 hour 1800 F)	Longitudinal	155	135	18
	Transverse	154	142	13
	Transverse	155	142	13
Recrystallized	Longitudinal	120	104	29
(1 hour 2200 F)	Longitudinal	120	107	28
	Transverse	120	105	26
	Transverse	121	106.5	26

(a) Crosshead speed 0.02 inch per minute up to yielding, and 0.05 inch per minute to fracture. Analyses 0.013% C, 0.005% N, 0.0088% O, and <0.0001% H.

TABLE A-32. COMPARISON OF ROOM-TEMPERATURE TENSILE PROPERTIES OF RECRYSTALLIZED Ta-Cb-V ALLOY SHEET(a)(2)

Alloy Composition	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
Ta-32Cb-5.1V(b)	Longitudinal	98	80.5	32
(1 hour 2300 F;	Longitudinal	100	80	25
0.040 Inch)	Longitudinal	105	87	26
	Transverse	100	77	28
	Transverse	110	89	26
	Transverse	104	85	18
	Average	103	83	26
Ta-28.8Cb-7.1V(c)	Longitudinal	120	104	29
(1 hour 2200 F;	Longitudinal	120	106	28
0.045 inch)	Transverse	120	105	26
	Transverse	121	107	26
	Average	120	105.5	27

(a) Crosshead speed 0.02 inch per minute up to yielding, and 0.05 inch per minute to fracture.
(b) Analyses 0.0025% C, 0.005% N, 0.0042% O, and 0.0002% H.
(c) Analyses 0.013% C, 0.005% N, 0.0088% O, and <0.0001% H.

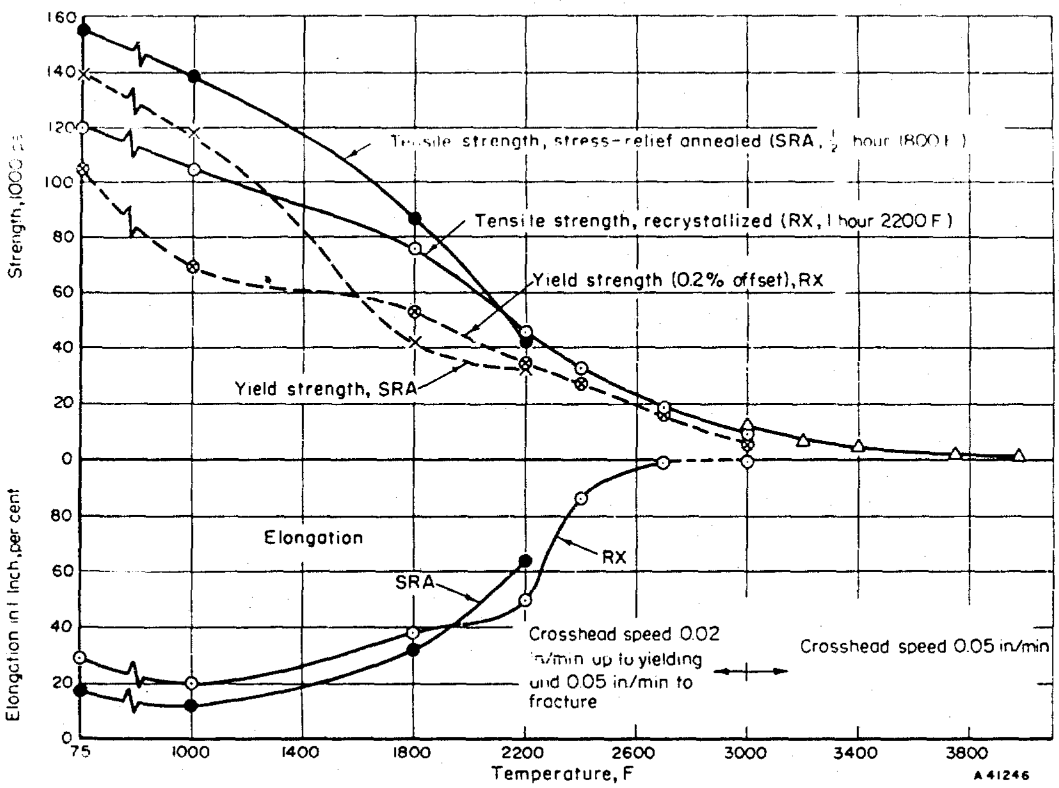

FIGURE A-45. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST Ta-28.8Cb-7.1V SHEET (0.045 INCH)[2,3]

Impurity	Weight Per Cent
C	0.013
N	0.005
O	0.0088
H	<0.0001

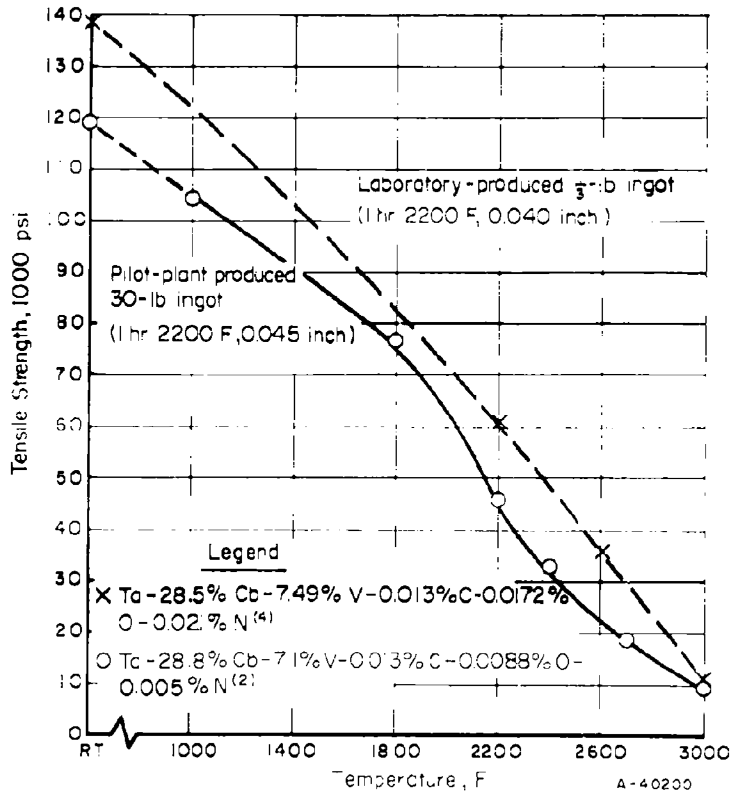

FIGURE A-46. STRENGTH COMPARISONS OF RECRYSTALLIZED Ta-Cb-V ALLOY SHEET PREPARED FROM 30- AND 1/3-POUND ARC-CAST INGOTS

4. Metallurgical Properties

a. Fabricability: extrusion temperatures should be on the order of 3200 to 3600 F; forging can readily be accomplished at 2200 to 2400[2], while rolling breakdown is conducted at about 1800 F[4]; final rolling, after intermediate annealing, is performed at room temperature[2, 4]

b. Transition temperature: <-320 F[2,4]

c. Weldability: inert-gas-fusion welds of sheet material present no problem. As-welded properties closely approximate those of the base metal at room temperature.[2]

d. Stress-relief temperature: 1/2 hour 1800 F[2]
1 hour 2010 F[4]

e. Recrystallization temperature:

Prior Cold Work, per cent reduction	1-Hr Recrystallization Temperature[2], F Ta-32Cb-5.1V[a]	Ta-28.8Cb-7.1V[b]
25	2300	2300
50	2200	2300
75	2100	2200

(a) 0.00025% C, 0.005% N, 0.0042% O, and 0.0002% H.
(b) 0.013% C, 0.005% N, 0.0088% O, and <0.0001% H.

Table A-33
Figure A-47

TABLE A-33. EFFECT OF TEMPERATURE AND COLD WORK ON THE RECRYSTALLIZED GRAIN SIZE OF Ta-28.8Cb-7.1V SHEET(a)(2)

[illegible] Per Cent Cold Worked			50 Per Cent Cold Worked			75 Per Cent Cold Worked		
1-Hour Annealing Temperature, F	Hardness, VHN(b)	Average Grain Diameter, mm	1-Hour Annealing Temperature, F	Hardness, VHN(b)	Average Grain Diameter, mm	1-Hour Annealing Temperature, F	Hardness, VHN(b)	Average Grain Diameter, mm
2200	291	PR(c)	2200	319	PR(c)	2200	218	0.035
2400	279	0.090	2400	267	0.055	2400	211	0.055
2600	285	0.110	2600	289	0.090	2600	225	0.090
3000	298	0.180	3000	297	0.150	3000	276	0.130
3500	295	>0.282	3500	285	>0.282	3500	229	>0.282

(a) Analyses 0.013% C, 0.005% N, 0.0088% O, <0.0001% H.
(b) 10-kg load.
(c) PR = partially recrystallized.

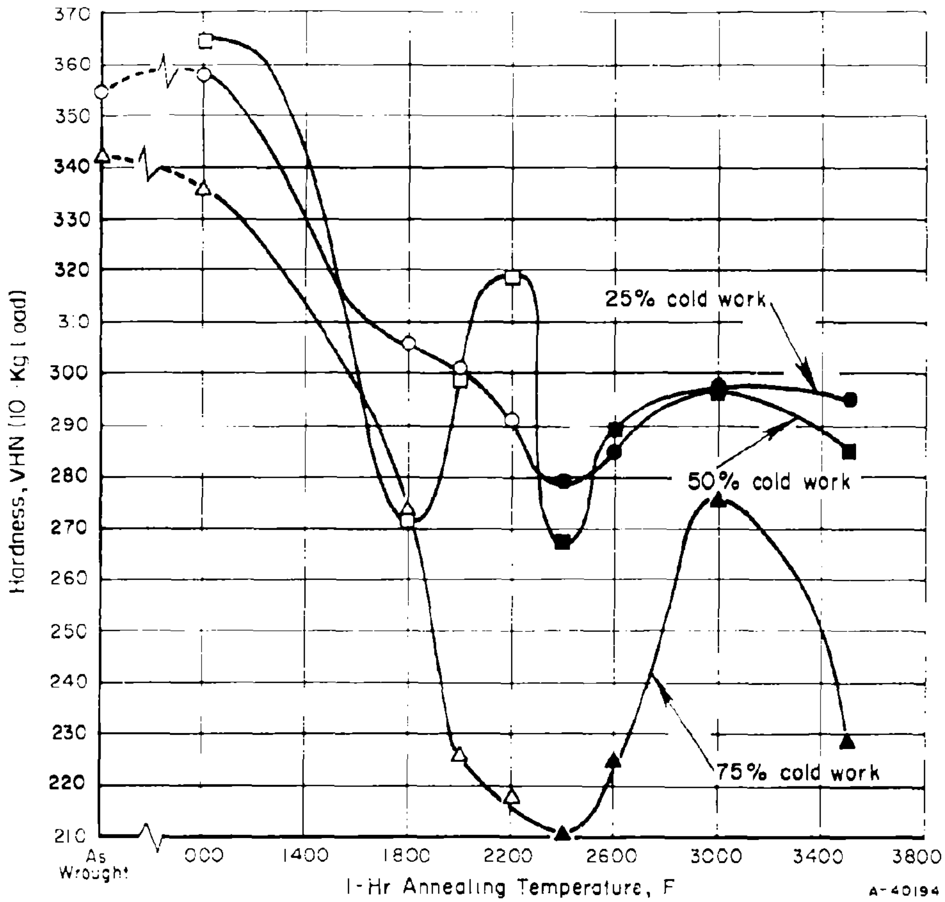

FIGURE A-47. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE HARDNESS OF Ta-28.8Cb-7.1V ALLOY

Solid symbols indicate complete recrystallization.

Impurity	Weight Per Cent
C	0.013
N	0.005
O	0.0065
H	<0.0001

References

(1) Unpublished data obtained under Contract AF 33(616)-7452, Battelle Memorial Institute (1961).

(2) Ogden, H. R., et al., "Scale-Up Development of Tantalum-Base Alloys", Battelle Memorial Institute, ASD TR 61-684 (November, 1961).

(3) Private communication from R. W. Hall of NASA Lewis Research Center to ASD (November 22, 1961).

(4) Schmidt, F. F., et al., "Investigation of the Properties of Tantalum and Its Alloys", Battelle Memorial Institute, WADD TR 61-106 (March, 1960).

Ta-5W-2.5Mo

1. Identification of Material

   a. Chemical composition: Ta-5W-2.5Mo

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Density: 0.595 lb/in.^{3} (calculated)

2. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-34

      Tensile yield strength: Table A-34

      Elongation: Table A-34

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-35
Figure A-48

      Tensile yield strength: Table A-35
Figure A-48

      Elongation: Table A-35

   c. Creep and Stress-Rupture Properties

      Figure A-49

   d. Other Selected Mechanical Properties

      Bend ductility: reverse bend testing for annealed 0.040-inch sheet material[1]

Number of Successful Bending Operations Before Fracture, Bend Axis, Relative to Final Rolling Direction

Transverse		Parallel	
Forward[a]	Reverse[b]	Forward[a]	Reverse[b]
2-4	1-3	2-4	2-3

(a) Bent around 0 T radius (<0.0156 inch) through a 105-degree angle.
(b) Flattened to original condition by pressing in a vise.

Table A-36

TABLE A-34. ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST Ta-5W-2.5Mo SHEET (0.040 INCH)[a][1]

Rolling Direction Relative to Extrusion Direction	Rolling Procedure	Rolling Temp, F	No. of In-Process Anneals	Final Rolling Reduction, per cent	Tensile Strength, 1000 psi		Yield Strength (0.2% Offset), 1000 psi		Elongation in 1/2 Inch, per cent	
					Long.	Transverse	Long.	Transverse	Long.	Transverse
⊥	Straight	800	0	90	98.9	100.8	94.1	96.6	36	37
⊥	Straight	1000	0	90	99.4	102.3	99.2	100.4	37	36
	Cross	800 and 1000	0	90	100.0	102.7	91.9	96.6	36	36
	Cross	800 and 1000	0	90	96.7	96.5	89.0	88.5	35	38
	Cross	800	1	65	102.6	105.3	90.4	98.7	37	38
	Cross	800	1	35	101.6	103.8	88.0	94.4	36	34
	Cross	800	3	35	103.9	105.7	94.5	96.8	32	34

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F. Test rate 0.005 inch per inch per minute to 0.6 per cent yield, and 0.25 inch per inch per minute to fracture.

Typical analyses of extruded bar:[2]

Weight Per Cent		PPM			
W	Mo	C	O	N	H
4.6	2.5	4	166	35	2

TABLE A-35. TENSILE PROPERTIES OF ARC-CAST Ta-5W-2.5Mo SHEET (0.040 INCH) AT 2700 F[a][1]

Rolling Direction Relative to Extrusion Direction	Rolling Procedure	Rolling Temp, F	No. of In-Process Anneals	Final Rolling Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1/2 Inch, per cent
⊥	Straight	1000	0	90	20.7	19.5	84
	Cross	800 and 1000	0	90	22.2	20.7	82
	Cross	800 and 1000	0	90	20.7	19.8	86
	Cross	800	1	65	20.4	18.9	84
	Cross	800	1	35	22.4	20.6	76
	Cross	800	3	35	21.9	19.9	80

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F. Test rate 0.025 inch per inch per minute.

Typical analyses of extruded bar:[illegible]

Weight Per Cent		PPM			
W	Mo	C	O	N	H
[illegible]	[illegible]	4	[illegible]	35	2

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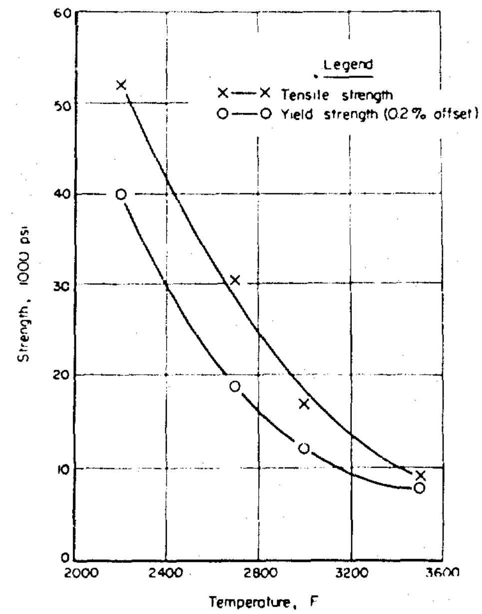

FIGURE A-48. EFFECT OF TEMPERATURE ON THE STRENGTH OF ANNEALED (1 HOUR, 2550 F) Ta-5 W-2.5 Mo SHEET (0.040 INCH)(3)

Laboratory-produced button ingot.

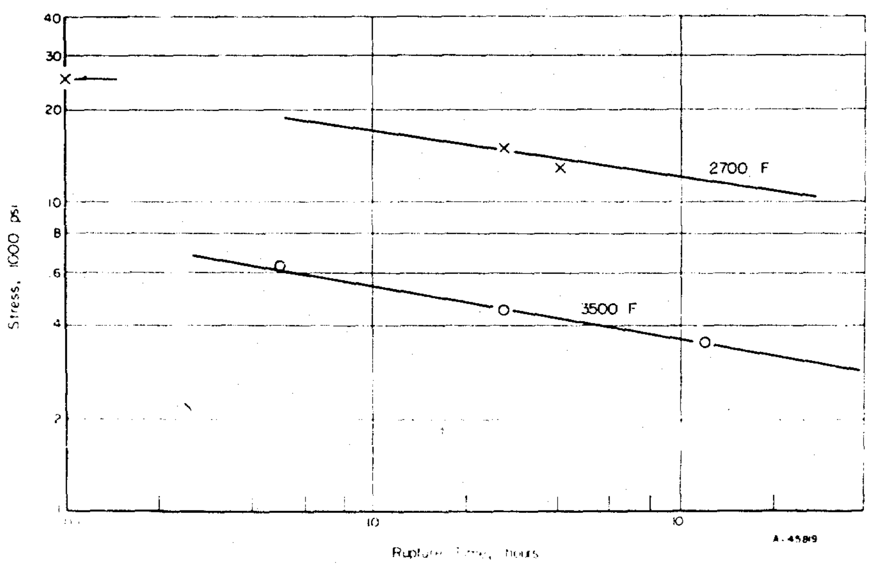

FIGURE A-49. HIGH-TEMPERATURE RUPTURE CHARACTERISTICS OF ANNEALED (1 HOUR, 2550 F) Ta-5 W-2.5 Mo SHEET (0.040 INCH)(4)

Laboratory-produced button ingot.

TABLE A-36. EFFECTS OF ROLLING HISTORY AND ANNEALING ON THE ROOM-TEMPERATURE BEND DUCTILITY OF ARC-CAST Ta-5W-2.5Mo SHEET (0.040 INCH)(1)

Prior History	Rolling Temperature, F	Room-Temperature Minimum Bend Radius, T Value(a): As-Wrought Condition, Longitudinal	As-Wrought Condition, Transverse	Stress-Relief Annealed 1 Hr at 2000 F, Longitudinal	Stress-Relief Annealed 1 Hr at 2000 F, Transverse	Recrystallize Annealed 1 Hr at 2600 F, Longitudinal	Recrystallize Annealed 1 Hr at 2600 F, Transverse
	90 Per Cent Finish Reduction: Straight Rolled; No In-Process Anneals						
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800(b)	1-3	10-13	0	0	0	0
Ditto	1000(b)	1-3	7-9	0	0	0	0
"	800(c)	3-4	8-13	0	0	0	0
	90 Per Cent Finish Reduction: Cross Rolled;(d) No In-Process Anneals						
Ditto	800-1000	0-2	1-4	0	0	0	0
Extruded 2600 F; forged 2300 F, 1 hr 2800 F	800-1000	1-3	4-5	0	0	0	0
	65 Per Cent Finish Reduction: Cross Rolled;(d) One In-Process Anneal						
Extruded 2600 F; 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800	0-3	2-3	0	0	0	0
	35 Per Cent Finish Reduction: Cross Rolled;(d) One In-Process Anneal						
Ditto	800	0-2	0-2	0	0	0	0
	35 Per Cent Finish Reduction: Cross Rolled;(d) Three In-Process Anneals						
Ditto	800	2-4	0	0	0	0	0

(a) Values obtained from two to four tests for each condition cited.
(b) Rolled perpendicular to the original extrusion direction.
(c) Rolled parallel to the original extrusion direction.
(d) Equal reductions in original length and width dimensions before annealing.

Typical analyses of extruded bar:(2)

Weight Per Cent: W	Mo	PPM: C	O	N	H
4.[illegible]	[illegible]	4	166	35	2

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4. Metallurgical Properties

a. Fabricability: ingots can be successfully extruded at 2600 F followed by forging at 2200 to 2300 F; after conditioning and process annealing, rolling to sheet is performed at 800 to 1000 F[1,2]; after breakdown, final sheet rolling has been conducted at room temperature[3]

b. Transition temperaure: <-320 F for annealed 0.040-inch sheet material[3]

c. Weldability: annealed 0.050-inch sheet material can readily be joined by either inert-gas tungsten-arc or electron-beam processes; welds are room-temperature ductile[4]

d. Stress-relief temperature: 1 hour at 2000 F[1,3]

e. Recrystallization temperature: Tables A-37 and A-38

TABLE A-37. EFFECT OF ANNEALING TREATMENTS ON THE RECRYSTALLIZATION AND GRAIN SIZE OF EXTRUDED AND FORGED SHEET BARS[2]

Prior History	Per Cent Recrystallization After Annealing 1-Hour at Indicated Temperature, F: As Forged	2400	2600	2700	2800	3000	1-Hour Recrystallization Temperature, F	ASTM Grain-Size Range After Annealing 1 Hour: 2800 F	3000 F	Mean ASTM Grain Size After Annealing 1 Hour: 2800 F	3000 F
Extruded 2600 F; forged 2200 F	0	2	75	100	100	100	2700	3-8	1-7	6.3	5.6
Extruded 2600 F; recrystallized 1 hour, 3000 F; forged 2300 F	0	2	30	75	90	100	~2900	3-8	2-7	6.2	6.0
Extruded 2600 F; recrystallized 1 hour, 3000 F; forged 2200 F	0	0	75	95	100	100	2800	3-8	2-7	6.7	5.8

Typical analyses of extruded bar:

Weight Per Cent: W	Mo	PPM: C	O	N	H
4.6	2.5	4	166	35	2

TABLE A-38. RECRYSTALLIZATION AND HARDNESS OF ARC-CAST Ta-5W 2.5Mo SHEET (0.040 INCH)[a][2]

Rolling Temperature, F	Total Reduction, per cent	Approximate 1-Hour Recrystallization Temperature, F	Hardness, VHN: Initial	As Wrought	Annealed 1 Hour: 2000 F	2600 F
800	45	2600	241	369	--	240
800	70	2500	241	384	--	246
800	85	2400	241	388	--	245
800	90	2400	241	395	348	242
1000	90	2400	241	410	350	243

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F.

Typical analyses of extruded bar:

Weight Per Cent: W	Mo	PPM: C	O	N	H
[illegible]	[illegible]	4	[illegible]	[illegible]	2

References

(1) Maykuth, D. J., Hallowell, J. B., and Ogden, H. R., "Tantalum-Alloy-Processing Development", Battelle Memorial Institute, Contract No. AF 33(657)-8911, ASRCT TR 7-781 (IV) (June 1, 1963).

(2) Maykuth, D. J., and Ogden, H. R., "Tantalum-Alloy-Processing Development", Battelle Memorial Institute, Contract No. AF 33(657)-8911, ASRCT TR 7-781 (III) (March 1, 1963).

(3) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594 (July, 1962).

(4) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594 (Part II) (May, 1963).

Ta-8W-2Hf

1. Identification of Material

   a. Designation: T-111 (Westinghouse)

   b. Chemical composition: the base composition has been made with varying interstitial contents; however, moderate and low interstitial grades can be identified as follows:[1]

Element	Weight Per Cent Moderate	Weight Per Cent Low
W	7.0-9.0	7.0-9.0
Hf	2.0-2.8	2.0-2.8
O (nominal)	0.010	0.003
N (nominal)	0.007	0.003
C (nominal)	0.003	0.001
Ta	Bal.	Bal.

   c. Forms available: plate, sheet, strip, foil, bar, wire, and tubing[1]

2. Physical Properties

   a. Melting point: 5400 F (estimated)[1]

   b. Density: 0.604 lb/in.^{3}[1]

   c. Thermal expansion: Table A-39
      Figure A-50

   d. Electrical resistivity: Figure A-51

TABLE A-39. COEFFICIENT OF THERMAL EXPANSION OF T-111[1]

Temperature		Coefficient of Thermal Expansion	
F	C	10^{-6} In./In./F	10^{-6} In./In./C
80-500	25-260	3.1	5.5
80-1000	25-540	3.5	6.3
80-1500	25-815	3.9	7.0
80-2000	25-1095	3.9	7.0
80-2500	25-1365	4.0	7.2
80-3000	25-1650	4.2	7.5
80-3500	25-1925	4.2	7.5
80-4000	25-2205	4.2	7.6
80-4350	25-2400	4.3	7.8

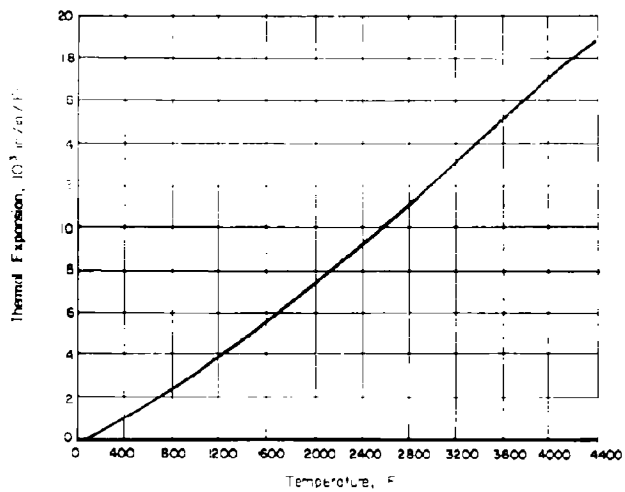

FIGURE A-50. THERMAL EXPANSION OF T-111[2]

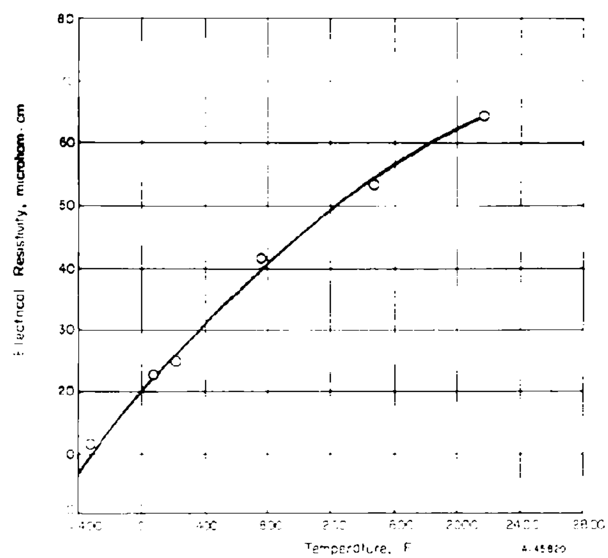

FIGURE A-51. ELECTRICAL RESISTIVITY OF RECRYSTALLIZED T-111[2]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-40

Tensile yield strength: Table A-40

Elongation: Table A-40

Modulus of elasticity: $28-30 \times 10^6$ psi[3]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-41 and A-42

Tensile yield strength: Tables A-41 and A-42

Elongation: Tables A-41 and A-42

c. Creep and Stress-Rupture Properties

Table A-43

TABLE A-40. ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-MELTED T-111 SHEET

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reference
Stress-relieved sheet (3 hr 2250 F, 0.040 inch)(a)	112.3(L) 113.7(T)	96.0(L) 100.7(T)	21.8(L) 17.9(T)	(3) (3)
Stress-relieved sheet (1 hr 2000 F)(b)	150.0	144.8	9.0	(1)
Stress-relieved sheet (1 hr 2000 F)(c)	135.0	130.0	15.0	(1)
Recrystallized sheet (1 hr 3000 F)(b)	90.4	90.4	29.0	(1)

(a) Test rate 0.005 inch per inch per minute to 0.6 per cent offset, and 0.05 inch per inch per minute to fracture. Analyses 7.8% W, 1.95% Hf, 0.0027% C, 0.0023% O, 0.0026% N, 0.0035% Fe, 0.0008% Cr, 0.0005% Ni, and 0.0100% Mo.

(b) Low interstitial grade. Cold rolled 90 per cent prior to final annealing. Test rate 0.005 inch per inch per minute through 0.2 per cent yield strength, and 0.05 inch per inch per minute to fracture.

(c) Moderate interstitial grade. Warm rolled 95 per cent prior to final annealing. Test rate 0.04 to 0.06 inch per inch per minute.

TABLE A-41. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST T-111 SHEET (0.040 INCH)(a)(3)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
2400	40.0	33.1	41.7
3000	20.3	17.9	29
3500	11.2	11.2	31

(a) Stress-relieved 3 hours at 2250 F. Test rate 0.[illegible]5 inch per inch per minute. Analyses 7.8% W, 1.95% Hf, 0.0027% C, 0.0023% O, 0.0020% N, 0.0035% Fe, 0.0008% Cr, 0.0005% Ni, and 0.0100% Mo.

TABLE A-42. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST LOW AND MODERATE INTERSTITIAL-GRADE T-111 SHEET

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
	Low Interstitial Grade, Cold Rolled 90 Per Cent, Stress Relieved 1 Hour at 2000 F[a]		
-452	--	232.2	0.3[b]
-320	194.5	188.5	12.6
-100	--	157.7	--
75	150.0	144.8	9.0
400	124.0	121.6	4.0
800	114.8	111.6	3.6
2000	92.1	67.5	8.0
2200	67.1	52.2	20.0
2400	42.4	38.6	28.0
2400[c]	50.7	43.8	26.0
2700	25.4	21.0	76.0
3000	16.3	14.1	52.0
3500	11.3	10.9	43.0
	Low Interstitial Grade, Cold Rolled 90 Per Cent, Recrystallized 1 Hour at 3000 F[a]		
-452	187.7	--	17.5
-300	150.6	145.2	27.0
-100	108.8	93.8	24.0
75	90.4	90.4	29.0
400	68.0	68.0	23.0
800	57.2	43.0	15.5
2000	61.1	34.9	18.0
2200	49.3	28.6	25.0
2400	37.3	23.5	36.0
2700	30.9	24.4	30.0
3000	14.8	11.9	48.0
3500	13.0	12.6	34.0
	Moderate Interstitial Grade, Warm Rolled 95 Per Cent, Stress Relieved 1 Hour at 2000 F[d]		
-320	190.0	184.0	18.0
-100	150.0	146.0	17.0
75	135.0	130.0	15.0
2200	85.0	78.0	15.0
2400	57.6	49.5	24.7
2500	54.0	38.0	26.0
2700	29.0	23.7	64.0
3000	20.5	19.5	60.0
	Moderate Interstitial Grade, Warm Rolled 95 Per Cent, Recrystallized 1 Hour at 3000 F[d]		
3000	17.2	17.2	46.0

(a) Test rate at -452 to 800 F 0.005 inch per inch per minute through 0.2 per cent yield, and 0.5 inch per inch per minute to fracture; above 800 F, 0.04 to 0.06 inch per inch per minute.

(b) Ductile fracture, 41 per cent reduction in area.

(c) Cold rolled 65 per cent.

(d) Test rate 0.04 to 0.06 inch per inch per minute.

TABLE A-13. STRESS-RUPTURE PROPERTIES OF ARC-CAST T-111 SHEET AT 2400 F

Condition	Stress, 1000 psi	Time to Rupture, hours	Elongation, per cent	Reference
Stress-relieved sheet (3 hr 2250 F, 0.040 inch)[a]	35.0	0.5	--	(3)
	33.0	0.8	--	
	30.0	7.3	--	
	25.7	5.0	--	
	23.0	5.0	--	
	20.0	19.8	--	
Stress-relieved sheet (reduced 65 per cent, 1 hr 2000 F)[b]	30.0	2.3	50	(1)
	25.0	4.3	58	
	20.0	25.7	94	
Recrystalled sheet (reduced 80 per cent, 1 hr 3000 F)[b]	35.0	3.0	30	(1)
	25.0	7.3	40	

(a) Analyses 7.8% W, 1.95% Hf, 0.0027% C, 0.0023% O, 0.0026% N, 0.0035% Fe, 0.0008% Cr, 0.0005% Ni, and 0.0100% Mo.

(b) Low interstitial grade.

4 Metallurgical Properties

a. Fabricability: ingot breakdown temperatures should be above 2000 F, while intermediate fabrication can be conduced at somewhat lower temperatures.[4] Final forming such as punching, blanking, shearing, bending, brake forming, drawing, and spinning can be performed at room temperature without edge cracking.[1]

b. Transition temperature: <-452 F[1]

c. Weldability: inert-gas fusion welding has been used exclusively in welding T-111. In addition to sheet butt welds, half-tube to half-tube seam welds have been made. T-111 has also been welded to columbium alloys. Helium welding atmospheres have proved to be more satisfactory than argon with regard to as-welded ductility. Weld-ductility at -200 F is essentially the same as that for the base metal.[1]

d. Stress-relief temperature 1 hour 2400 F[1]
3 hours 2250 F[3]

e. Recrystallization temperature: Table A-44

TABLE A-44. RECRYSTALLIZATION BEHAVIOR OF ARC-CAST T-111 SHEET[1]

Annealing Temperature, F	50% Cold Work		75% Cold Work		90% Cold Work	
	Hardness	Recrystallization[a], %	Hardness	Recrystallization[a], %	Hardness	Recrystallization[a], %
As worked	353	0	370	0	375	0
2000	361	0	373	0	360	0
2200	340	0	350	0	335	0
2400	295	0	305	0	295	0
2600	287	0	282	0	245	50
2800	270	50	263	50	232	100
3000	277	100	270	100	259	100

(a) Metallographic determination.

References

(1) "T-111, Tantalum Base Alloy Refractory Metal", Westinghouse Electric Corp., Special Technical Data 52-363 (March, 1963).

(2) Ammon, R. L., and Begley, R. T., "Pilot Production and Evaluation of Tantalum Alloy Sheet", Westinghouse Electric Corp., Contract NOw-62-0656-d, Quarterly Report No. 3 (February 16, 1963).

(3) National Research Corp., Data Sheet on Ta-10W and Ta-8W-2Hf Alloy Sheet (May 2, 1963).

(4) Unpublished data obtained under Contract AF 33(616)-7688, Battelle Memorial Institute (1962).

Ta-10W-2.5Hf

1. Identification of Material

   a. Designation: T-222 (Westinghouse)

   b. Chemical composition: Ta-10W-2.5Hf

   c. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Density: 0.604 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-45

      Tensile yield strength: Table A-45

      Elongation: Table A-45

      Reduction in area: Table A-45

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-46

      Tensile yield strength: Table A-46

      Elongation: Table A-46

      Reduction in area: Table A-46

TABLE A-45. ROOM-TEMPERATURE TENSILE PROPERTIES OF RECRYSTALLIZED T-222 SHEET(a)(1)

Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Total Elongation, per cent	Reduction in Area, per cent
110.0	105.0	25	--
110.6	100.2	30	63

(a) Data for same material, two different tests. Material reduced 90 per cent, recrystallized 1 hour at 3000 F. Test rate 0.005 inch per inch per minute. Analyses 9.5% W, 2.44% HF, 0.011% C, 0.0029% O, and 0.0034% N.

TABLE A-46. LOW- AND HIGH-TEMPERATURE TENSILE PROPERTIES OF T-222 SHEET(a)(1)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Total Elongation, per cent	Reduction in Area, per cent
		Reduced 90 Per Cent, Stress Relieved 1 Hour at 2000 F		
1800	112.3	107.0	6	--
2000	100.0	89.2	10	--
2200	78.8	68.8	18	--
		Reduced 90 Per Cent, Recrystallized 1 Hour at 3000 F		
-320	184.6	175.0	28	51
75	110.0	105.0	25	--
75	110.6	100.2	30	63
2000	77.6	40.3	18	--
2200	67.3	38.4	17	--
2400	53.4	37.8	20	--
2600	36.8	29.3	34	--
2800	30.5	27.7	48	--
3000	24.9	24.1	24	--
3500	14.2	14.2	43	--

(a) Test rate 0.005 inch per inch per minute for -320 and 75 F tests, and 0.05 inch per inch per minute for all other tests. Analyses 9.5% W, 2.44% HF, 0.011% C, 0.0029% O, and 0.0034% N.

4. Metallurgical Properties

a. Fabricability: arc-cast ingots can be forged directly in a dynamic argon atmosphere at 2200 F; after conditioning and recrystallizing for 1 hour at 3000 F the forged slabs can be cold rolled 5 to 10 per cent per pass to high-quality sheet (0.040 to 0.050-inch sheet)[2]

b. Transition temperature: <-320 F for sheet material reduced 90 per cent and recrystallized 1 hour at 3000 F[1]

c. Stress-relief temperature: 1 hour at 2000 F for material reduced 90 per cent[1]

d. Recrystallization temperature: 1 hour at 3000 F for material reduced 90 per cent[1]

References

(1) Private communications from R. L. Ammon, Westinghouse Electric Corporation.

(2) Ammon, R. L., and Begley, R. T., "Pilot Production and Evaluation of Tantalum Alloy Sheet", Westinghouse Electric Corporation, Contract N600 (19) 59762, Quarterly Report No. 4 (August 15, 1963).

Ta-10W-2.5Mo

1. Identification of Material

   a. Chemical composition: Ta-10W-2.5Mo

   b. Forms available: ingot and fabricated shapes available from suppliers on a best efforts basis

2. Physical Properties

   a. Density: 0.599 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-47

      Tensile yield strength: Table A-47

      Elongation: Table A-47

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-48
      Figure A-52

      Tensile yield strength: Table A-48
      Figure A-52

      Elongation: Table A-48

   c. Creep and Stress-Rupture Properties

      Figure A-53

   d. Other Selected Mechanical Properties

      Bend ductility: reverse bend testing for annealed 0.040-inch sheet material(1)

      Number of successful bending operations before fracture: bend axis, relative to final rolling direction

Transverse		Parallel	
Forward[a]	Reverse[b]	Forward[a]	Reverse[b]
2-3	1-2	2-4	1-3

(a) Bent around 0 T radius (~0.0150 inch) through a 105-degree angle.
(b) Flattened to original condition by pressing in a vise.

Table A-49

TABLE A-47. ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST Ta-10W-2.5Mo SHEET (0.040 INCH)[a][1]

Rolling Direction Relative to Extrusion Direction	Rolling Procedure	Rolling Temp, F	No. of In-Process Anneals	Final Rolling Reduction, per cent	Tensile Strength, 1000 psi		Yield Strength (0.2% Offset), 1000 psi		Elongation in 1/2 Inch, per cent	
					Long.	Transverse	Long.	Transverse	Long.	Transverse
⊥	Straight	800	0	90	111.0	113.1	106.6	107.5	34	38
⊥	Straight	1000	0	90	110.0	112.3	102.3	104.3	36	36
	Cross	800 and 1000	0	90	111.1	112.8	102.5	107.1	36	34
	Cross	800 and 1000	0	90	111.7	114.6	104.7	107.6	35	38
	Cross	800	1	65	111.6	115.1	103.8	110.1	36	36
	Cross	800	1	35	120.1	118.8	111.[illegible]	111.4	28	31
	Cross	800	3	35	117.9	116.7	105.2	[illegible]	30	31

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F. Test rate 0.005 inch per inch per minute to 0.6 per cent yield, and 0.25 inch per inch per minute to fracture.

Typical analyses of extruded bar:(2)

Weight Per Cent		PPM			
W	Mo	C	O	N	H
9.6	2.5	7	107	37	1

TABLE A-48. TENSILE PROPERTIES OF ARC-CAST Ta-10W-2.5Mo SHEET (0.040 INCH) AT 2700 F[a][1]

Rolling Direction Relative to Extrusion Direction	Rolling Procedure	Rolling Temp, F	No. of In-Process Anneals	Final Rolling Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1/2 Inch, per cent
⊥	Straight	800	0	90	26.7	24.9	70
⊥	Straight	1000	0	90	25.6	23.4	86
	Cross	800 and 1000	0	90	28.3	25.2	78
	Cross	800 and 1000	0	90	27.2	24.4	76
	Cross	800	1	65	26.2	25.6	88
	Cross	800	1	35	31.6	28.8	68
	Cross	800	3	35	29.8	26.5	66

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F. Test rate 0.025 inch per inch per minute.

Typical analyses of extruded bar:(2)

Weight Per Cent		PPM			
W	Mo	C	O	N	H
9.6	2.5	7	107	37	1

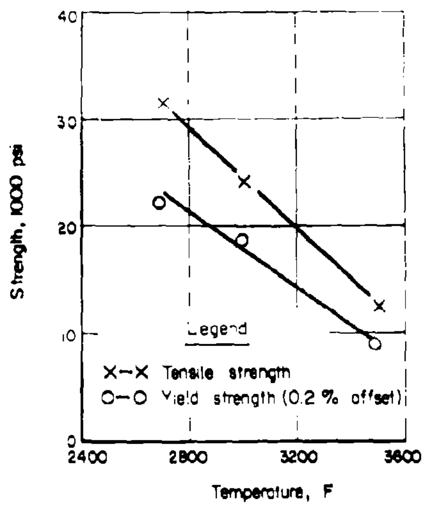

FIGURE A-52. EFFECT OF TEMPERATURE ON THE STRENGTH OF ANNEALED (1 HOUR, 3090 F) Ta-10 W-2.5 Mo SHEET (0.040 INCH)(3)

Laboratory-produced button ingot.

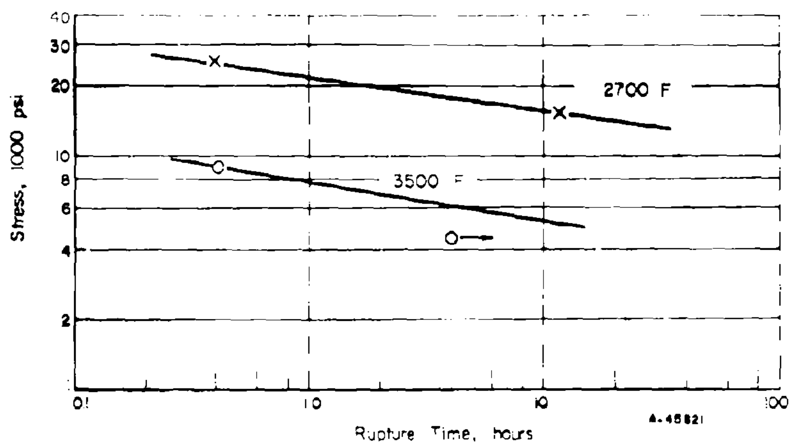

FIGURE A-53. HIGH-TEMPERATURE RUPTURE CHARACTERISTICS OF ANNEALED (1 HOUR, 3090 F) Ta-10 W-2.5 Mo SHEET (0.040 INCH)(4)

Laboratory-produced button ingot.

TABLE A-[illegible]. EFFECTS OF ROLLING HISTORY AND ANNEALING ON THE ROOM-TEMPERATURE BEND DUCTILITY OF ARC-CAST Ta-10W-2.5Mo SHEET (0.040 INCH)[1]

Prior History	Rolling Temp, F	Room-Temperature Minimum Bend Radius, T Value[a]: As-Wrought Condition, Long.	As-Wrought Condition, Transverse	Stress-Relief Annealed 1 Hr at 2000 F, Long.	Stress-Relief Annealed 1 Hr at 2000 F, Transverse	Recrystallize Annealed 1 Hr at 2600 F, Long.	Recrystallize Annealed 1 Hr at 2600 F, Transverse
90 Per Cent Finish Reduction: Straight Rolled; No In-Process Anneals							
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800[b]	3-4	6-9	0-1	0-1	0	0
Ditto	1000[b]	0-2	5-7	0	0	0	0
"	800[c]	0-1	6-7	0-1	0-1	0-1	0-1
90 Per Cent Finish Reduction: Cross Rolled;[d] No In-Process Anneals							
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800-1000	1-4	3-5	0	0	0	0
Extruded 2600 F; forged 2200 F, 1 hr 2800 F	800-1000	2-3	2-3	0-1	0-1	0	0
65 Per Cent Finish Reduction: Cross Rolled;[d] One In-Process Anneal							
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800	1-5	0-3	0	0	0	0
35 Per Cent Finish Reduction: Cross Rolled;[d] One In-Process Anneal							
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	800	1-4	1-3	0	0	0	0
35 Per Cent Finish Reduction: Cross Rolled;[d] Three In-Process Anneals							
Extruded 2600 F, 1 hr 3000 F; forged 2300 F, 1 hr 2800 F	[illegible]	3-7	5-7	[illegible]	0	[illegible]	0

(a) Values obtained from 2 to 4 tests for each condition cited.
(b) Rolled perpendicular to the original extrusion direction.
(c) Rolled parallel to the original extrusion direction.
(d) Equal reductions in original length and width dimensions before annealing.

Typical analyses of extruded bar:[2]

Weight Per Cent: W	Weight Per Cent: Mo	PPM: C	PPM: O	PPM: N	PPM: H
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

4. Metallurgical Properties

a. Fabricability: ingots can be successfully extruded at 2000 F followed by forging at 2200 to 2300 F; after conditioning and process annealing, rolling to sheet is performed at 800 to 1000 F[1,2]

b. Transition temperature: ~-150 F for annealed 0.040-inch sheet material[4]

c. Weldability: annealed 0.050-inch sheet material can readily be joined by either inert-gas tungsten-arc or electron-beam processes; welds are room-temperature brittle[1]

d. Stress-relief temperature: 1 hour at 2000 F[1]; 1 hour at 2370 F[3]

e. Recrystallization temperature: Tables A-50 and A-51

TABLE A-5[illegible]. EFFECT OF ANNEALING TREATMENTS ON THE RECRYSTALLIZATION AND GRAIN SIZE OF EXTRUDED AND FORGED SHEET BARS(2)

Prior History	Per Cent Recrystallization After Annealing 1 Hour at Indicated Temp, F: As Forged	2400	2600	2700	2800	3000	1-Hour Recrystallization Temp, F	ASTM Grain-Size Range After Annealing 1 Hour at Indicated Temp, F: 2800	3000	Mean ASTM Grain Size After Annealing 1 Hour at Indicated Temp, F: 2800	3000
Extruded 2600 F, forged 2200 F	0	0	10	98	1000	100	2800	3-9	3-8	7.0	6.8
Extruded 2600 F, recrystallized 1 hour 3000 F, forged 2300 F	0	0	10	70	95	100	~2900	3-8	3-7	7.1	6.3
Extruded 2600 F, recrystallized 1 hour 3000 F, forged 2200 F	0	0	20	70	95	100	~2900	4-8	2-7	7.5	5.7

Typical analyses of extruded bar:

Weight Per Cent: W	Mo	PPM: C	O	N	H
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE A-51. RECRYSTALLIZATION AND HARDNESS OF ARC-CAST Ta-10W-2.5Mo SHEET (0.040 INCH)(a)(2)

Rolling Temperature, F	Total Reduction, per cent	Approximate 1-Hour Recrystallization Temperature, F	Hardness, VHN: Initial	As Wrought	Annealed 1 Hour: 2000 F	2600 F
800	45	2600	267	379	--	267
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	[illegible]
800	85	2600	267	401	--	284
800	90	2500	267	428	374	273
[illegible]	[illegible]	[illegible]	267	[illegible]	382	[illegible]

(a) Extruded at 2600 F and forged to sheet bar at 2200 to 2300 F.

Typical analyses of extruded bar:

Weight Per Cent: W	Mo	PPM: C	O	N	H
9.6	2.5	[illegible]	107	37	1

References

(1) Maykuth, D. J., Hallewell, J. B., and Ogden, H. R., "Tantalum-Alloy-Processing Development", Battelle Memorial Institute, Contract No. AF 33(657)-8911, ASRCT TR 7-781 (IV) (June 1, 1963).

(2) Maykuth, D. J. and Ogden, H. R., "Tantalum-Alloy-Processing Development", Battelie Memorial Institute, Contract No. AF 33(657)-8911, ASRCT TR 7-781 (III) (March 1, 1963).

(3) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594 (July, 1962).

(4) Schmidt, F. F., et al., "Investigation of Tantalum and Its Alloys", Battelle Memorial Institute, ASD-TDR-62-594 (Part II) (May, 1963).

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46D	Department of Defense Titanium Sheet-Rolling Program – Uniform Testing Procedure for Sheet Materials, September 12, 1958 (PB 121649 $1.25)
46E	Department of Defense Titanium Sheet-Rolling Program – Thermal Stability of the Titanium Sheet-Rolling-Program Alloys, November 25, 1958 (PB 151061 $1.25)
46F	Department of Defense Titanium Sheet-Rolling Program Status Report No. 4, March 20, 1959 (PB 151065 $2.25)
46G	Department of Defense Titanium Sheet-Rolling Program – Time-Temperature-Transformation Diagrams of the Titanium Sheet-Rolling Program Alloys, October 19, 1959 (PB 151075 $2.25)
46H	Department of Defense Titanium Sheet-Rolling Program, Status Report No. 5, June 1, 1960 (PB 151087 $2.00)
46I	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V Sheet, September 16, 1960 (PB 151095 $1.25)
46J	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V and Ti-2.5Al-16V Sheet, June 6, 1961 (AD 259284 $1.25)
106	Beryllium for Structural Applications, August 15, 1958 (PB 121648 $3.00)
107	Tensile Properties of Titanium Alloys at Low Temperature, January 15, 1959 (PB 151062 $1.25)
108	Welding and Brazing of Molybdenum, March 1, 1959 (PB 151063 $1.25)
109	Coatings for Protecting Molybdenum From Oxidation at Elevated Temperature, March 6, 1959 (PB 151064 $1.25)
110	The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al), April 17, 1959 (PB 151066 $3.00)
111	The Physical Metallurgy of Precipitation-Hardenable Stainless Steels, April 20, 1959 (PB 151067 $2.00)
112	Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels, May 1, 1959 (PB 151068 $3.25)
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114	Ductile-Brittle Transition in the Refractory Metals, June 25, 1959 (PB 151070 $2.00)
115	The Fabrication of Tungsten, August 14, 1959 (PB 151071 $1.75)
116R	Design Information on 5Cr-Mo-V Alloy Steels (H-11 and 5Cr-Mo-V Aircraft Steel) for Aircraft and Missiles (Revised), September 30, 1960 (PB 151072-R $1.50)
117	Titanium Alloys for High-Temperature Use Strengthened by Fibers or Dispersed Particles, August 31, 1959 (PB 151073 $2.00)
118	Welding of High-Strength Steels for Aircraft and Missile Applications, October 12, 1959 (PB 151074 $2.25)
119	Heat Treatment of High-Strength Steels for Aircraft Applications, November 27, 1959 (PB 151076 $2.50)
120	A Review of Certain Ferrous Castings Applications in Aircraft and Missiles, December 18, 1959 (PB 151077 $1.50)
121	Methods for Conducting Short-Time Tensile, Creep, and Creep-Rupture Tests Under Conditions of Rapid Heating, December 20, 1959 (PB 151078 $1.25)
122	The Welding of Titanium and Titanium Alloys, December 31, 1959 (PB 151079 $1.75)
123	Oxidation Behavior and Protective Coatings for Columbium and Columbium-Base Alloys, January 15, 1960 (PB 151080 $2.25)
124	Current Tests for Evaluating Fracture Toughness of Sheet Metals at High Strength Levels, January 28, 1960 (PB 151081 $2.00)
125	Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, February 22, 1960 (PB 151082 $1.75)
126	Structural Damage in Thermally Cycled René 41 and Astroloy Sheet Materials, February 29, 1960 (PB 151083 $0.75)
127	Physical and Mechanical Properties of Tungsten and Tungsten-Base Alloys, March 15, 1960 (PB 151084 $1.75)
128	A Summary of Comparative Properties of Air-Melted and Vacuum-Melted Steels and Superalloys, March 28, 1960 (PB 151085 $2.75)
129	Physical Properties of Some Nickel-Base Alloys, May 20, 1960 (PB 151086 $2.75)
130	Selected Short-Time Tensile and Creep Data Obtained Under Conditions of Rapid Heating, June 17, 1960 (PB 151088 $2.25)
131	New Developments of the Welding of Metals, June 24, 1960 (PB 151089 $1.25)
132	Design Information on Nickel-Base Alloys for Aircraft and Missiles, July 20, 1960 (PB 151090 $3.00)
133	Tantalum and Tantalum Alloys, July 25, 1960 (PB 151091 $[illegible].00)
134	Strain Aging of Refractory Metals, August 12, 1960 (PB 151092 $1.75)
135	Design Information on [illegible] Stainless Steel for Aircraft and Missiles, August 22, 1960 (PB 151093 $1.25)

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136B	The Effects of Alloying Elements in Titanium, Volume B. Physical and Chemical Properties, Deformation and Transformation Characteristics, May 29, 1961 (AD 260226 $3.00)
137	Design Information on 17-7 PH Stainless Steels for Aircraft and Missiles, September 23, 1960 (PB 151096 $1.00)
138	Availability and Mechanical Properties of High-Strength Steel Extrusions, October 26, 1960 (PB 151097 $1.75)
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143	High-Strength-Steel Forgings, January 5, 1961 (PB 151102 $1.75)
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146	Manual for Beryllium Prospectors, January 18, 1961 (PB 151105 $1.00)
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167	Summary of the Fifth Meeting of the Refractory Composites Working Group, March 12, 1962 (AD 274804 $2.00)
168	Beryllium for Structural Applications, 1958-1960, May 18, 1962 (AD 278723 $3.50)
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175	Summary of the Sixth Meeting of the Refractory Composites Working Group, September 24, 1962 (AD 287029 $1.75)
176	Status Report No. 2 on Department of Defense Refractory Metals Sheet-Rolling Program, October 15, 1962 (AD 288127 $1.25)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. I (AD 294345 $3.00)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. II (AD 294346 $4.00)
178	Steels for Large Solid-Propellant Rocket-Motor Cases, November 20, 1962
179	A Guide to the Literature on High-Velocity Metalworking, December 3, 1962
180	Design Considerations in Selecting Materials for Large Solid-Propellant Rocket-Motor Cases, December 10, 1962
181	Joining of Nickel-Base Alloys, December 20, 1962
182	Structural Considerations in Developing Refractory Metal Alloys, January 31, 1963
183	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten (Supplement to DMIC Report 152), February 7, 1963
184	Summary of the Seventh Meeting of the Refractory Composites Working Group, May 30, 1963
185	The Status and Properties of Titanium Alloys for Thick Plate, June 14, 1963
186	The Effect of Fabrication History and Microstructure on the Mechanical Properties of Refractory Metals and Alloys, July 10, 1963
187	The Application of Ultrasonic Energy in the Deformation of Metals, August 16, 1963

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188	The Engineering Properties of Columbium and Columbium Alloys, September 6, 1963

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF TANTALUM AND TANTALUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 13, 1963. [112] pp incl. illus., tables, refs. DMIC Report 189. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering tantalum and seven of its alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

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1. Tantalum
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

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